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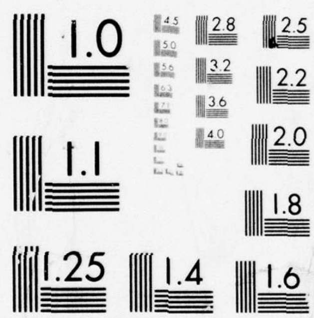
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

SENSITIVITY STUDY OF CONTROL PARAMETERS DURING UNDERWAY REPLENISHMENT SIMULATIONS INCLUDING APPROXIMATE NONLINEAR SEA EFFECTS

By

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and

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PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT

ANNAPOLIS

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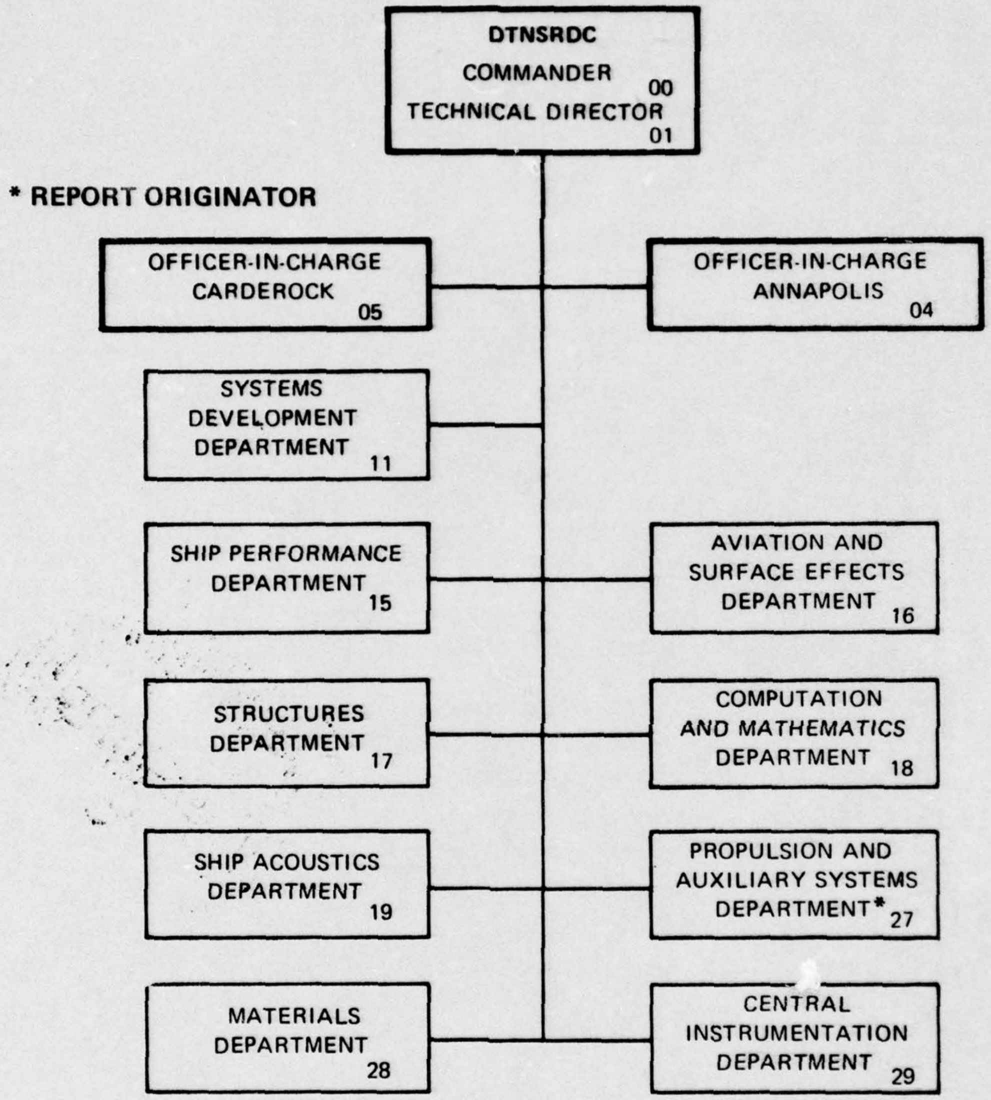

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This report describes the fourth phase of the development of a hybrid computer simulation of two ships during underway replenishment (UNREP) operations. Emphasis was placed on performing sensitivity analysis of the maneuvering control parameters. Some approximate nonlinear sea state excitations acting on the ships' hulls due to a specific irregular sea were added to the simulation model. The mathematical model for both the nonlinear force and moment excitations was developed by using the Volterra Series mathematical

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formalism. The forces and moments were represented during the simulation by time series. The sea state was defined in the UNREP simulation by the Pierson-Moskowitz Spectra.

The simulation incorporating some approximate nonlinear sea state excitations, together with an automatic controller on each ship, was used for control variable sensitivity studies. The automatic controllers were used to eliminate human bias. Simulated maneuvers included station keeping, station changing, and the approach and breakaway phases of standard Navy UNREP operations. Previous work showed that the control variables required for display included heading angle, heading angle rate, longitudinal separation distance, lateral separation distance, lateral separation distance rate, propeller shaft revolutions, and rudder angle. The sensitivity studies performed here revealed that measurement errors in the range of 3% to 5% in the control variables were acceptable under the conditions of the simulation.

The good controllability of both ships when using automatic control during UNREP simulations indicated that automatic control should be considered for collision avoidance during UNREP. The results of the simulation sensitivity control-variable analysis will be used for engineering judgments in developing a prototype sensing system for maneuvering control during UNREP. Two Mariner Class Study ships were used in the study but the simulation technique can be easily adapted to Navy ships by incorporating the appropriate hydrodynamic data.

ADMINISTRATIVE INFORMATION

This report satisfies milestone 1 of Fiscal Year 1977, Work Unit Summary, Shipboard Machinery and Control-Monitoring and Automation of 15 February 1977. This work was funded by NAVSEA under Element 62543, Task Area SF 43-433-302, Work Unit 2730-100, Task 19296.

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Mr. Gary L. Stump of the Propulsion and Auxiliary Systems Department of the Center for validating and documenting the computer programs used in the UNREP simulation. Mr. Arthur Chaikin, NAVSEA Program Manager, for continual encouragement and support.

LIST OF ABBREVIATIONS

DEG - degrees

DEG/S - degrees per second

FT - feet

FT/S - feet per second

Kn - knot

LB - pound

LB-FT - pound-feet

M - meters

M/S - meters per second

N - newtons

N-M - newton-meters

RAD - radians

RAD/S - radians per second

S - second

UNREP - underway replenishment

EXECUTIVE SUMMARY

INTRODUCTION

The operational procedure of replenishing ships at sea while steaming on parallel courses in close proximity is used extensively by the Navy. Since fuel and/or cargo must be transferred, a suitable physical connection must be maintained, thus increasing the danger of collision between the ships. The tracking ship is usually assigned the task of avoiding collision and maintaining station relative to the leading ship. The leading ship is assigned the task of maintaining a steady course and speed.

At the Center, data were collected from underway replenishment (UNREP) collision reports documented at the Naval Safety Center and the Fleet Material Support office. The data from these reports were analyzed to determine the principal causes of collisions, cost of repairs, and time out of service. Fleet personnel experienced in UNREP operations were interviewed and asked for suggestions relative to reducing the risk of collision.

From the study, it was determined that the monetary cost of ship repairs and the operational time lost by ships during repair warranted an analysis of the UNREP control problem. A need for more control information and/or instrumentation which would assist the Conning Officer and/or helmsmen was also apparent. Thus, it was decided to simulate two ships during UNREP maneuvering operations to establish, on a quantitative basis, the control parameters affecting ship control.

UNREP INVESTIGATION

The Center is conducting an investigation of the control problems involving the complex dynamic interaction between two ships maneuvering in close proximity during UNREP. The objective of this investigation is to define the necessary control parameters and recommend a prototype sensing system for ship control during UNREP maneuvering involving Naval ships. Definition of these control parameters aboard ship will aid the Conning Officer and/or helmsmen in preventing ship collisions.

APPROACH AND PROGRESS

The maneuvering control problem for UNREP was studied by developing and exercising a hybrid computer simulation. Two identical Mariner class merchant ships were used in the study because of insufficient hydrodynaic data for conventional Naval surface ships. However, the resultant simulation can easily be adapted to Naval ships when the hydrodynamic information becomes available. The simulation results for the Mariner and conventional Naval ships should, in general, be similar.

Phases I-III of the simulation study included the beginning development of a hybrid computer underway replenishment maneuvering simulation for two Mariner type ships. Simulation of UNREP in calm and regular seas where both rudder and propeller revolutions were "manually" controlled on each ship was performed in Phases I and II. In Phase III, an automatic control was incorporated into the simulation together with linear irregular sea effects in the sway and yaw degrees of freedom. The control variables to be displayed aboard ship were determined to be heading angle, heading angle rate, longitudinal and lateral separation distance, lateral separation rate, propeller shaft revolutions, and rudder angle. The relatively high-frequency linear, first-order sway force (and yaw moment) were determined not to be a control problem under the conditions of the simulation. The present Phase IV simulation work emphasized the use of an automatic controller on each ship for maneuvering control variable sensitivity studies. Using an automatic controller on each ship was one way to eliminate subjective results due to the skills of the operators when using manual control. Some approximate nonlinear sea excitations were added to the simulation model as an engineering approximation to an irregular sea state. The irregular sea state (Note: 4 or 5 on Beaufort Scale, moderate sea state) is defined by the Pierson-Moskowitz Spectrum. The UNREP simulation model has some limitations so that simulation results may be provisional. These simulation studies indicated that sensor noise and measurement errors of approximately 3% to 5% in the maneuvering control variables should be acceptable for a ship-separation monitoring system under the conditions of the simulation. Despite the obvious limitations of the mathematical model on the UNREP simulation the results presented here should be useful for engineering judgments in designing a sensor system for maneuvering control during UNREP.

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that this investigation be continued to simulate Naval ships during UNREP. At the Massachusetts Institute of Technology, computerized analytical techniques for determining the interaction forces and moments for surface ships due to close proximity maneuvers such as UNREP have been developed and will be incorporated into this work. Hydrodynamic maneuvering coefficients for Navy ships (i.e., the DD 963 Destroyer and AO 177 Class Auxiliary Oiler) have been determined by model testing experiments by the Ship Performance Department.

Underway replenishment simulation with Naval ships should be performed with "Quickened Manual Control" and "Automatic Control." Comparisons of these different control methods for UNREP maneuvering should be made. The studies should include different types of sensor systems and displays of measured control variables aboard Naval ships. It is anticipated that some of these sensing systems will be available on the latest Naval ships. From these studies, a prototype sensing system for UNREP should be recommended for Naval Ships.

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NOMENCLATURE

A	=	Longitudinal separation distance measured between centers of mass of the two ships
B	=	Lateral separation distance between the two ships (side-to-side distance)
a_T	=	Gain constant in integral feedback loop
$F^{(n)}$	=	Term n in functional series
g	=	Gravitational constant
$H(\omega)$	=	First-order (linear) transfer function
$H(\omega_1, \omega_2)$	=	Second-order transfer function
h	=	Wave height (crest to trough) for regular wave
h_n	=	nth-order impulse response function
$\dot{I}m$	=	Imaginary part
I_z	=	Moment of inertia about z axis
K	=	Kernal of integral equation
$\underline{K_L}$	=	Feedback gain vector for leading ship
$\underline{K_T}$	=	Feedback gain vector for tracking ship
L	=	Ship length between perpendiculars (LBP)
m	=	Mass of ship
n_1	=	Initial propeller r/min (ahead straight-line motion)
Δn	=	$n - n_1$ (n - propeller r/min)
N	=	Yawing moment about z axis
r	=	Angular velocity of yaw ($r = \dot{\psi}$)
$R\varepsilon$	=	Real part
$R_{xxx}(\tau_1,\tau_2)$	=	Cross-covariance function for processes X and Y
$S_{xxy}(\omega_1,\omega_2)$	=	Physically realizable cross-bi-spectral density function
$S_X(\omega)$	=	Pierson-Moskowitz Spectrum

$t, \Delta t$ = Time and time interval, respectively

u, v = Velocity components of the origin of the body axes, (longitudinal and transverse components, respectively, corresponding to surge and sway velocity components)

u_1 = Initial equilibrium velocity component (ahead straight-line motion at constant speed with rudder at amidships

Δu = $u - u_1$

$\dot{u}, \dot{v}$ = Acceleration components of the origin of the body axes, (longitudinal and transverse components, respectively

$\vec{V}$ = Velocity vector of the origin of the body axes

x, y, z = Coordinate axes fixed in ship. Origin of axes system need not be at the center of gravity of the ship (positive direction forward, starboard, and downward, respectively)

x_0, y_0, z_0 = Coordinate system fixed with respect to the surface of the earth

$\overline{x}_0, \overline{y}_0, \overline{z}_0$ = Coordinates of the center of mass of the ship relative to the coordinate system fixed with respect to the surface of the earth

$X(t)$ = Free-surface elevation

X, Y = Hydrodynamic force components on ship body (longitudinal and lateral components, respectively)

ζ = Wave amplitude for regular wave

δ = Angular displacement of the rudder

$\varepsilon(\omega)$ = Random phase angle

λ = Wave length of regular wave

ρ = Water mass density

$\phi(\omega)$ = Phase of first-order system

$\phi(\omega_1, \omega_2)$ = Phase of second-order system

NOMENCLATURE (Continued)

ψ = Angle of yaw

χ = Ship-to-wave heading angle

ω = radian frequency

INTRODUCTION

GENERAL DISCUSSION OF UNDERWAY REPLENISHMENT

Replenishment operations are conducted at sea by the Navy to transfer cargo or fuel between ships. This extends the operational time of ships at sea. During replenishment, a suitable physical connection must be maintained between the ships which are maneuvering on essentially parallel courses at the same average speed. Since the ships are close together during the physical connection, there is danger of collision. The tracking ship usually has the task of avoiding collision while maintaining station relative to the leading ship which attempts to maintain steady course and speed.

During Underway Replenishment (UNREP) operations, the conning officer on the tracking ship monitors both relative speed and separation distance between the ships. A marked distance line is used to measure the distance between the two ships. One end of this line is attached to the leading ship, while the other end is tended by a man on the tracking ship. He pays out and takes up the line as required to keep it "taut". The conning officer orders small course and speed changes to maintain position. Details of UNREP operations have been published.[1-5]

UNDERWAY REPLENISHMENT COLLISIONS

Data were collected from UNREP collision reports documented in the Naval Safety Center and in Casualty Reports to Fleet Material Support Office. These data were analyzed to determine the principal causes of the collisions, dollar cost of repairs, and ship's time out of service. It was determined that the monetary cost of ship repairs and the operational time lost by the ships from service warranted an analysis of the maneuvering-control problem during UNREP. The results of the initial studies indicated that there was a need for more control information and/or instrumentation to assist the conning officer and/or helmsmen.

In addition, Fleet personnel experienced in UNREP operations were interviewed and asked for suggestions pertaining to reducing the risk of collision. In the opinion of ship handlers, the conning officer needs to know hull-to-hull distance between ships, whether the ships are opening or closing, the ordered course and rpm, and the rudder angle the helmsman is carrying to maintain course. The conning officer gets this information from the seaman's eye, the distance line, and the rudder-angle indicator. During the approach, the most critical stage of an UNREP, they use the radian rule, a maneuvering board, and a stadimeter.

BACKGROUND

The control problem involving the complex dynamic interaction between two ships maneuvering in close proximity during UNREP has been under investigation at the Center. The objective is to define and analyze maneuvering control parameters and recommend a prototype sensing system for ship control during UNREP. Selection and display of available control parameters for monitoring aboard Navy ships by the conning officers and/or helmsmen should reduce the collision hazard, increase the efficiency, and extend the range of operating conditions under which UNREP can be performed.

Phases I through III included the beginning development of a hybrid computer underway replenishment maneuvering simulation for two Mariner type ships. Simulation of UNREP in calm and regular seas was performed where both the rudder angle and propeller shaft revolutions were "manually" controlled on each ship.[6-8] Finally, an automatic controller on each ship was incorporated into the simulation.[9]

UNDERWAY REPLENISHMENT INVESTIGATION

This report describes the fourth phase of the development of the hybrid computer simulation for maneuvering during UNREP using the characteristics of two Mariner class merchant ships. Naval ships were not simulated because of insufficient hydrodynamic data for the conventional surface ships of interest. The computer program developed here can easily be adapted to Naval Surface ships. Similar simulation results can be expected for Naval ships where the response times to changes in propeller shaft revolutions and changes in rudder angle will differ somewhat from the Mariner.

During UNREP maneuvering simulations, the leading ship sets a straight-line course at constant speed and the tracking ship tries to maintain station relative to the leading ship.

This work emphasized the use of an automatic controller on each ship, which was developed earlier for sensitivity studies of maneuvering control variables. Using an automatic controller on each ship was one way to eliminate subjective results due to the skills of the "operators" when using manual control. Some approximate nonlinear sea excitations on the ships' hulls during UNREP were added to the simulation model as an engineering approximation of an irregular sea state. It was necessary in this work to get an indication of the performance of the controller on each ship when subjected to nonlinear sea state excitations. The irregular sea state is defined by the Pierson-Moskowitz wave energy spectrum which is a function of wind speed. The unidirectional sea state wave height as a function of time is represented by the Gaussian stochastic integral representation.

Since the object of UNREP maneuvering is to maintain a lateral and longitudinal separation between two ships traveling on essentially parallel courses, the sway and yaw degrees of freedom were considered most important. The roll and pitch motions were neglected in the UNREP simulation because they have insignificant effects on lateral separation distance and would have added unnecessary complexity to the simulation model. The present application involves the hypothesis that the sway force and yaw moment acting on a ship hull in oblique irregular waves can each be mathematically represented by an infinite functional power series.[10,11] The first-order (with respect to wave amplitude) sway and yaw terms of the series generally contain many relatively high-frequency as well as low-frequency components and are a zero-mean process. It is assumed in this work that "automatic control" is generally not required to compensate for the first-order irregular sway force (and yaw moments). This assumption may not be entirely realistic for control of two interacting ships. More work is needed in this area. The assumption is justified to some extent because in earlier work[8,9] they were determined not to be a control problem for either "manual" or automatic control under the conditions of the simulation. However, in future work, these terms can easily be incorporated into the UNREP simulation model. The second-order force and moment functions each contain two terms: (1) a low-frequency non-zero-mean component; and, (2) a high frequency zero-mean component. The high-frequency components are neglected because they are small, relatively high-frequency, zero-mean processes.

The slowly-varying transfer function of the second-order term of the Volterra Series was approximated. Newman suggested that the transfer function could be approximated throughout the bi-frequency plane by its diagonal value.[11] Thus, the approximate nonlinear transfer function associated with the slowly varying, second-order sway force (or yaw moment) was obtained by plotting the curve of the mean sway force (or yaw moment) developed on a ship model at a particular speed in a specified oblique regular wave divided by the wave amplitude, squared, versus wave encounter frequency. These data were obtained from model testing at the Stevens Institute of Technology by Chey[12] on a restrained Series 60 model in oblique regular waves.

After incorporating the approximate irregular sea state into the UNREP simulation, determination of the control variables and their sensitivities to measurement error using automatic control was made. Throughout this work the automatic controller on each ship demonstrated good performance and was relatively insensitive to errors in control variable measurement under the simulation conditions.

The nonlinear sea-state excitations on the ships' hulls simulated here have definite limitations and should not be considered as highly accurate, but only as an engineering approximation to give an indication

of random nonlinear sea effects on the automatic controller on each ship. The technique used to simulate the sea-state excitations uses the Pierson-Moskowitz Spectrum to define the sea state so that the nonlinear sway and yaw excitations can be related to the sea state characteristics.

Linear maneuvering equations for each ship were used as the basis of the UNREP simulation maneuvering mathematical model. Nonlinear hydrodynamic coefficients are of some importance (e.g., cross-flow drag) and cannot be totally ignored, but were not considered here. The first reason is that during the simulation conditions the two ships traveled on essentially straight line course at nearly the same speed (15 knots) in a rather moderate sea state (4 on the Beaufort Scale). Second, funding limitations and time did not allow a detailed analysis to be performed to determine which nonlinear hydrodynamic maneuvering coefficients are of importance under the simulation conditions presented here. In future UNREP simulation studies using Navy ships, however, it is planned to incorporate important nonlinear hydrodynamic coefficients into the maneuvering equations.

Since the controllers are relatively insensitive to changes of a number of orders of magnitude in the second-order, slowly varying force (or yaw moment) excitations, the automatic controllers would probably control both ships quite well if nonlinear maneuvering coefficients were added to the maneuvering equations under the conditions of the simulation.

Despite the obvious limitations of the mathematical model in the UNREP simulation, the results presented here should be useful for engineering judgments in designing a prototype sensor system for maneuvering control during UNREP.

UNREP SIMULATION IN IRREGULAR SEAS

The fourth phase of the UNREP simulation incorporates some approximate nonlinear irregular sea-state excitations on the ships' hulls and the hydrodynamic interaction forces and moments acting on both the leading and tracking ships (see figure 1). The UNREP simulation is capable of controlling either the leading or tracking ship's rudder and propeller shaft speed "manually" or "automatically," but only automatic control is considered in this phase for lateral control.

BASIC MATHEMATICAL MODEL

The ship dynamics model for each of the two identical Mariners used in this study consists of a set of linearized equations in the horizontal plane (surge, sway, and yaw). The nonlinear hydrodynamic interaction forces and moments and the nonlinear effects of the oblique irregular unidirectional sea (4 on Beaufort scale) are added to the model as additional forces and moments. The nonlinear equations for the leading ship are presented below (' represents the non-dimensional value):

Surge Equation

$$(X'_{\dot{u}} - m')\,\dot{u}' + X'_u \Delta u' = -X'_n \Delta n' \tag{1.1}$$

Sway Equation

$$(Y'_{\dot{v}} - m')\,\dot{v}' + Y'_v v' + (Y'_{\dot{r}} - m'x'_G)\,\dot{r}' \tag{1.2}$$

$$+ (Y'_r - m'u'_1)\,r' = -Y'_\delta \delta - Y'_n \Delta n' - Y'(A, B) - Y'_S(\chi)$$

Yaw Equation

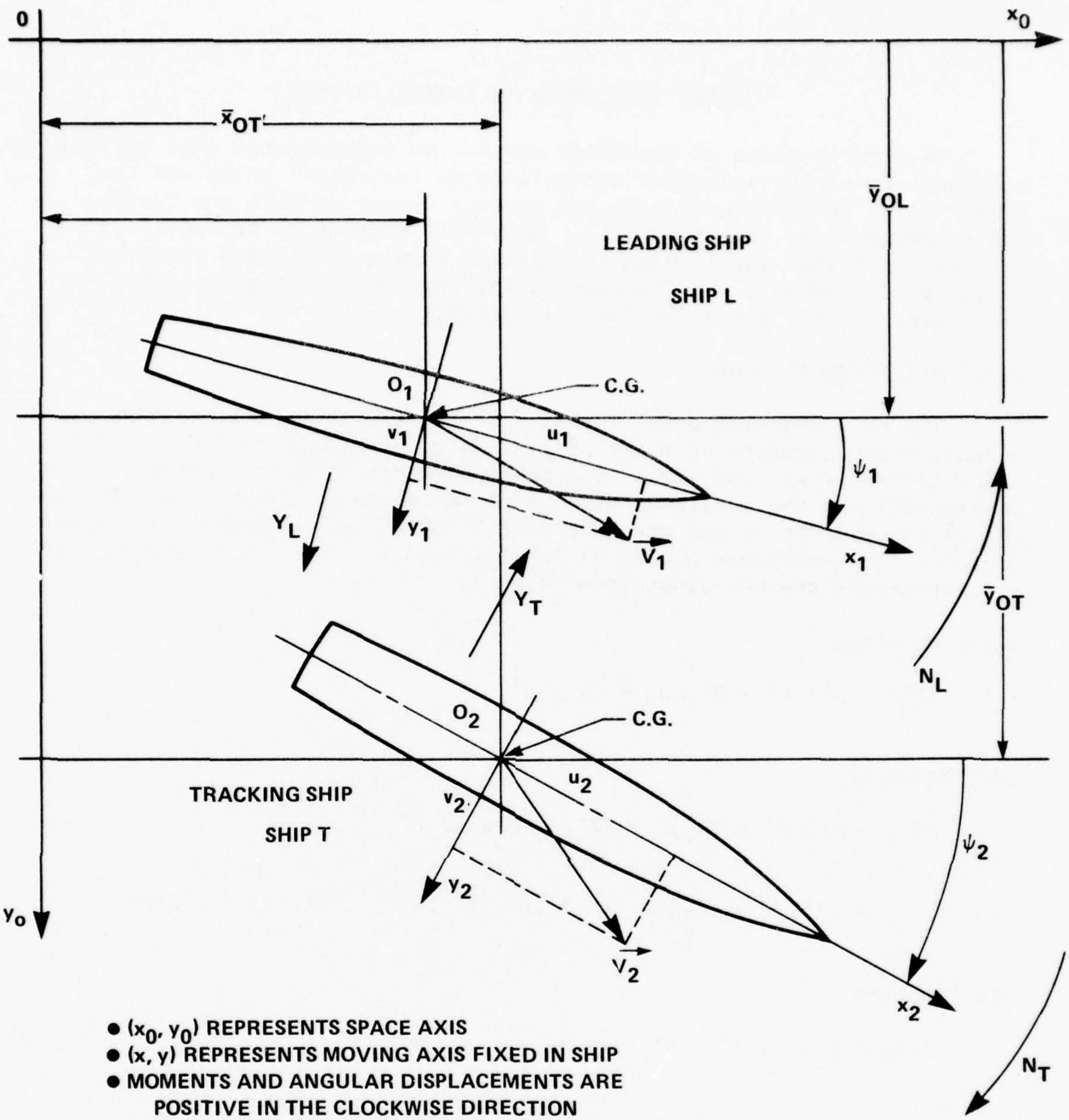
$$(N'_{\dot{v}} - m'x'_G)\,\dot{v}' + N'_v v' + (N'_{\dot{r}} - I'_z)\,\dot{r}' \tag{1.3}$$

$$+ (N'_r - m'x'_G u'_1)\,r' = -N'_\delta \delta - N'_n \Delta n' - N'(A, B) - N'_S(\chi)$$

where:

$Y'(A, B)$ = nondimensional hydrodynamic interaction force caused by tracking ship on the leading ship

$N'(A, B)$ = nondimensional hydrodynamic interaction moment caused by tracking ship on the leading ship



- (x_0, y_0) REPRESENTS SPACE AXIS
- (x, y) REPRESENTS MOVING AXIS FIXED IN SHIP
- MOMENTS AND ANGULAR DISPLACEMENTS ARE POSITIVE IN THE CLOCKWISE DIRECTION
- FORCES, DISPLACEMENTS, AND VELOCITY COMPONENTS ARE POSITIVE ALONG THE FORWARD DIRECTIONS OF THE ARROWS ALONG THE AXIS (x, y) FIXED IN SHIP

NOTE: The tracking ship is nearly abeam of the leading ship, and both ship's speeds are approximately 15 knots.

Figure 1
Orientation of the Leading and Tracking Ships During UNREP

$Y'_S(\chi)$ = nondimensional slowly varying, second-order sway force due to sea state (ship-to-wave angle $\chi = 150°$ (2.618 rad), (see figure 2)

$N'_S(\chi)$ = nondimensional slowly varying, second-order yaw moment due to sea state (ship-to-wave angle $\chi = 150°$ (2.618 rad), (see figure 2).

$Y'(A, B)$ and $N'(A, B)$ depend on the longitudinal separation, A, measured between centers of mass of two ships and lateral side-to-side distance, B, measured between two ships centers of mass. Since the study ships are identical, the interaction force $Y'(A, B)$, and moment $N'(A, B)$ are changed to $-Y'(-A,B)$ and $-N'(-A, B)$ when applied to the tracking ship's maneuvering equations. A and B are constantly calculated and updated in the simulation.

The following limitations exist and basic assumptions were made in developing the UNREP mathematical model:

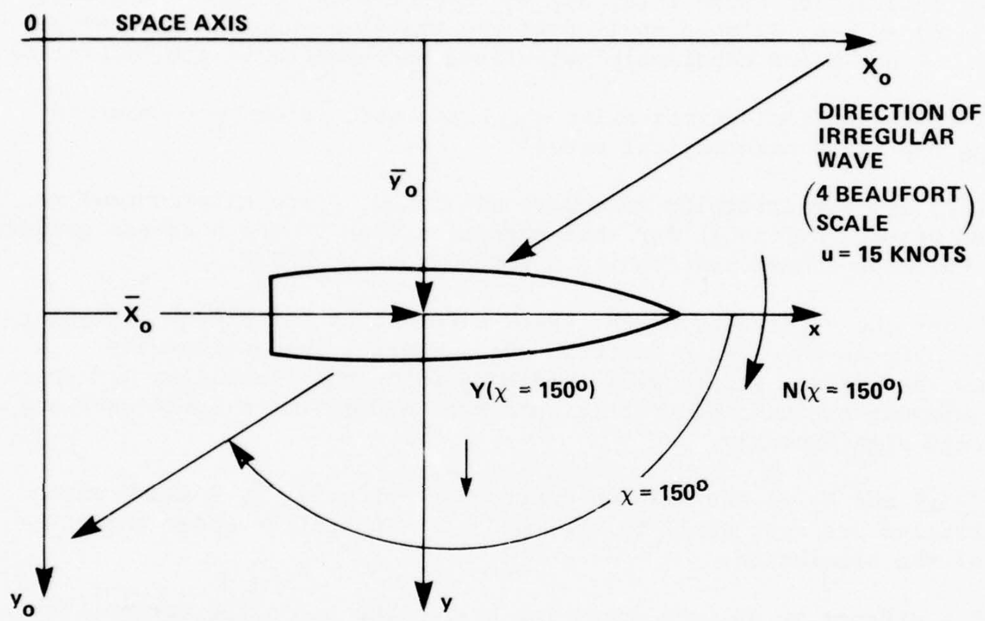
- Only oblique irregular seas were simulated, since ship control is assumed to be more difficult for this condition than in the head-sea condition which is the most common sea condition for performing UNREP.

- Under the conditions of the UNREP simulations in oblique irregular waves, the ship-to-wave angle for both ships changes insignificantly. If higher wave-height sea states were incorporated in the simulation and appropriate nonlinear maneuvering coefficients were added, the ship-to-wave angle could change significantly.

- $Y_S(\chi)$ and $N_S(\chi)$ are assumed independent of v, $\dot{v}$, $\dot{u}$, $\dot{\psi}$ and $\ddot{\psi}$ since these variables are kept small by the automatic controller under the conditions of the simulation.

- The effects of oblique irregular sea on the propeller (propeller loading) and power plant, which affect the ship's longitudinal control during maneuvering, are small. The reliability of X_n, Y_n and N_n obtained from calculations by Calvano[13] in open seas are uncertain under the conditions of the simulation. X_n was determined by using the effective horsepower versus propeller revolutions per minute data for a Mariner at speeds of approximately 15 knots. Y_n was calculated from the fact that a single screw Mariner requires a 1.2 degree port rudder to maintain a steady course in an open sea. From the value of Y_δ and assuming the force exerted by the propeller can be expected to vary as the propeller speed squared Y_n was calculated. The value of N_n was similarly obtained.

One should bear in mind, however, that the propeller performance in a calm-water condition and in a sea-state can be considerably different. Since there is no information available to the authors to judge the sensitivity of these terms with respect to the UNREP simulation, the relative importance of these terms to the other coefficients in the equations of motion cannot be determined.



NOTE: χ = Ship-to-Wave-Heading Angle

Figure 2
Orientation of Mariner Study Ship and Irregular Sea

• It is assumed that both ships are subjected to the same irregular wave system at any given instant of time. This assumption holds only when the sizes of the two ships are about the same size and the gaps between the two hulls are not so large compared to the average wave length.

• It is assumed that automatic control is generally not required to compensate for the first-order sway force (and yaw moment) under the conditions of the simulation, since these are zero-mean processes (with both low and high frequency components) which do not affect the mean course of the ship. This is probably an acceptable assumption for the single ship traveling on a straight line course. However, for the UNREP maneuvering operation where there are two interacting ships, the assumption of no automatic control may not be entirely realistic. This assumption may be justified to some extent because in the Phase II[8] and III[9] work, it was shown that the first-order sway force (and yaw moment) did not cause a control problem for either "manual" or automatic control. Also, the primary objective of the work presented here was to study the nonlinear sea excitations on the ship's hull on the automatic controller on each ship during UNREP.

This assumption does not apply to low-frequency, high-amplitude swell. Time series of the first-order sway force (and yaw moment) can easily be added to the maneuvering equations in future work.

After adding the hydrodynamic interaction forces and interaction moments Y(A, B) and N(A, B) to the linear maneuvering equations for each ship, the response of the system to sea state excitations (sway and yaw) becomes nonlinear from a control theory point of view. Thus, even though the first-order and second-order sway force (and yaw moment) excitations are additive in the nonlinear equations of motion, their responses are approximately the sum of the separate responses of each excitation term. Therefore, before firm conclusions can be drawn about the response of the automatic controller to the first-order and second-order excitations, it probably would be necessary to add both the first-order sway force (and yaw moment) time series to the equations of motion.

• Nonlinear terms such as "cross-flow-drag" effects ($Y_{v|v|}v|v|$) cannot be completely dropped from the maneuvering equations for each ship. When this <u>simulation technique</u> is used to simulate "real" Navy ships, it is planned to study these nonlinear maneuvering effects and introduce the appropriate nonlinear hydrodynamic coefficients into the linear maneuvering equations.

Even though the model has definite limitations, the major objective of this work is to get an indication of the performance of the automatic controller on both ships to nonlinear sea state excitations. The automatic controller performance data are then used to determine the sensitivity of the

maneuvering control variables. The provisional simulation results presented here will be used for engineering judgments in designing and building a prototype sensor system for maneuvering control during UNREP. The validity of these and earlier simulation results will be determined by comparing the results with full-scale sea trials using the prototype sensing system.

The variables in equation (1) are defined in the nomenclature. The nondimensional variables are defined in Appendix A. The linear hydrodynamic coefficients in equation (1) are also presented in Appendix A. Most of these coefficients (except for X_η, Y_η, and N_η from Calvano's work[13]) are averages of coefficients for a Mariner at 14 to 15 knots and determined from data presented at the Twelfth International Towing Tank Conference.[14] The basic Mariner study ship's characteristics are presented in Table 1. A detailed description of the mathematical model and computer simulation of two Mariner ships maneuvering during underway replenishment in calm seas, which forms a basis for the current work, has been presented by Alvestad and Brown.[8]

INTERACTION CURVES

The steady-state ship interaction curves used in equation (1) are for two Mariner ships (traveling at 15 knots) on different parallel paths. Figures 1-A and 2-A in Appendix A show curves of the Y force and N moment versus separation distance, respectively. In each of these figures, the curves for B = 50 ft (15.24 m) and B = 100 ft (30.48 m) were determined from model testing by Calvano[13], and the curves B = 110 ft (33.53 m) through B = 150 ft (45.72 m) were determined by extrapolation by the authors.[8] The effects of the yawing of either ship on the interaction forces and moments are neglected in the simulation because the interaction curves are measured for parallel paths for the two ships. Since transients are relatively small in this UNREP simulation, the steady state and transient interaction forces and moments are assumed to be approximately equal.

TABLE 1
CHARACTERISTICS OF MARINER-TYPE
STUDY SHIP

Length	527.8 ft	160.9 m
Beam	76.0 ft	23.2 m
Draft	29.75 ft	9.07 m
Displacement	16,800 tons	16.9×10^6 kg
Block Coefficient, C_b	0.6	0.6

The ship's coordinates are assumed to be at the ship's center of gravity (i.e., x_G, $y_G \approx 0$).

SIMULATION OF RUDDER DYNAMICS

The lag time in the rudder dynamics when a rudder angle (helm angle) is commanded is another important aspect of the maneuvering control problem which must be considered. Figure 3 shows the analog design, developed by C. L. Patterson, Jr. of the Center, that was used to represent the rudder dynamics in the simulation. δ^* represents the rudder command and δ the actual rudder angle. The rate of change of the rudder angle was assumed to be directly proportional to the negative of the error signal ($\dot{\delta} = -K\delta_e$). The rate constant K was set equal to 0.50 ($\frac{1}{sec}$) and the minimum error signal was 7 degrees (.122 rads). Figure 4 shows the response of the rudder to step inputs of the helm angle. A dead-band (±0.5 degrees) was not included in the simulation of the rudder dynamics, but will be incorporated in future work.

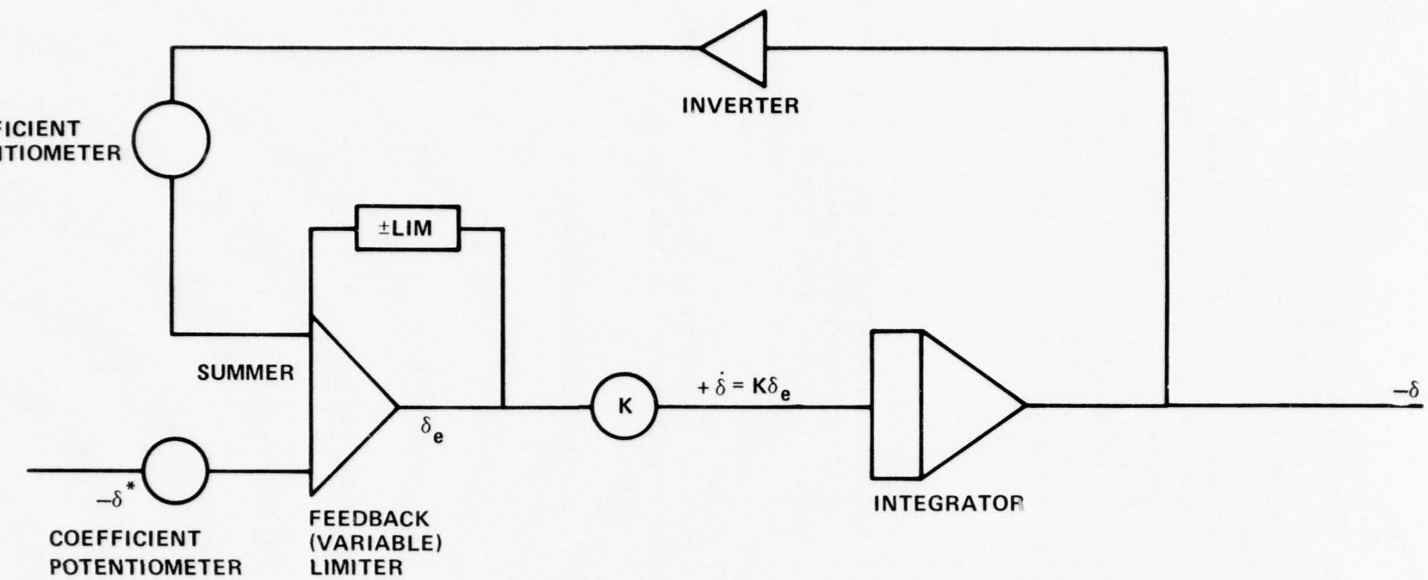
COORDINATE SYSTEMS

The coupled equations of planar motion are solved in ship velocity coordinates (u, v) and then transformed to the space coordinates (x_o, y_o), (see equation (2) and figure 1). This mathematical transformation was performed since the information of primary interest in an UNREP simulation is related to the space coordinates (i.e., longitudinal and lateral separation distances and yaw angle). In the work presented here, the space coordinate system is given an initial velocity of 15 knots, equal to the equilibrium velocity. Therefore, changes in the transverse and/or longitudinal position coordinates with respect to the space coordinates system (x_o, y_o) are due to perturbations above or below the ship equilibrium velocity.

The mathematical transformation from ship to space coordinates is representated by

$$\dot{x}_0 = u \cos \psi - v \sin \psi \tag{2}$$

$$\dot{y}_0 = u \sin \psi + v \cos \psi$$



δ^* = RUDDER COMMAND
δ_e = ERROR SIGNAL (MAXIMUM VALUE = 7°)
δ = ACTUAL RUDDER RESPONSE
K = 0.5/SEC
MAXIMUM RUDDER RATE = 3.5°/SEC

Figure 3
Analog Diagram Representing Rudder Dynamics

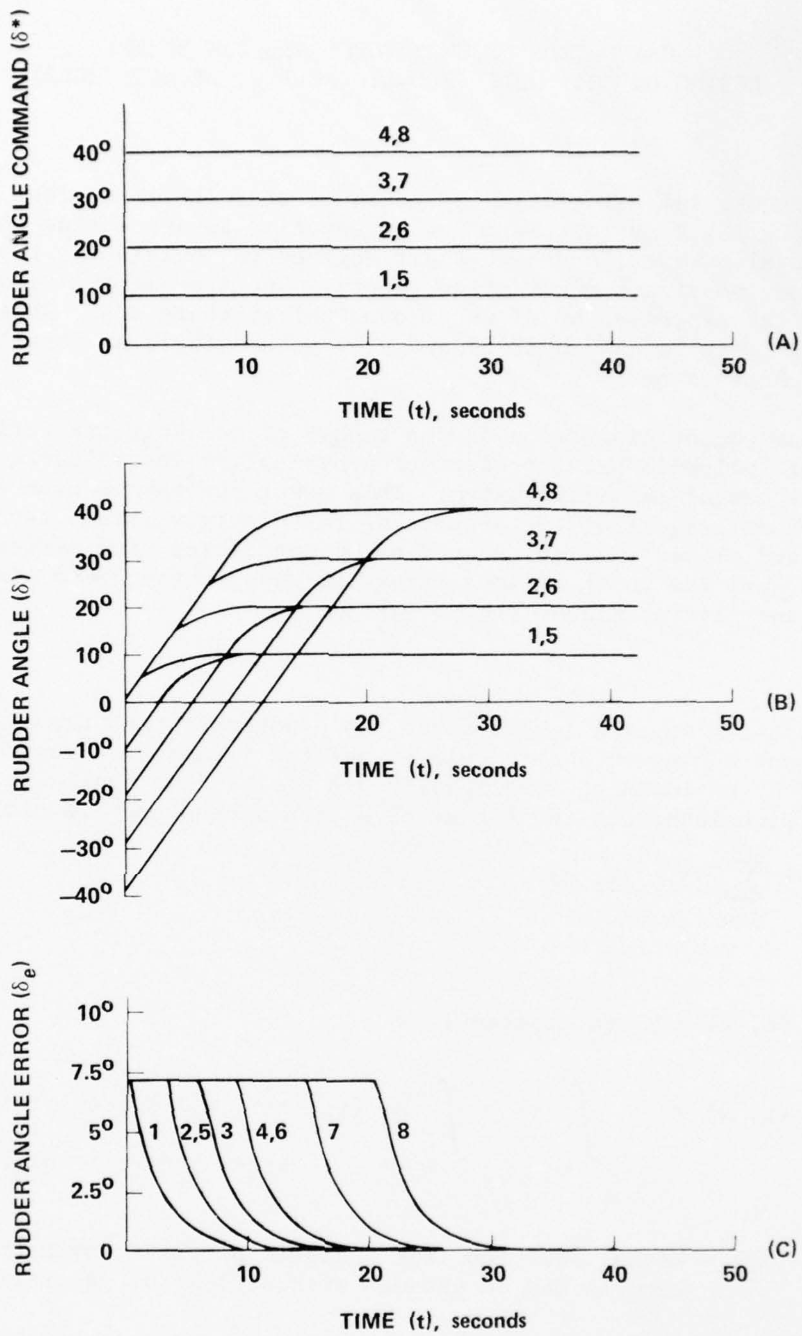


Figure 4
Response of Rudder System to Step Commands

GENERATION OF SWAY FORCE AND YAW MOMENT
ACTING ON SHIP HULL (SLOWLY VARYING, SECOND-ORDER)

BACKGROUND

The fundamental mathematical techniques of Volterra series were used for generating the sway force and yaw moment time series acting on the ship hull in irregular waves, and have their engineering origins in the field of electrical engineering communication theory. The fundamental ideas used here were first expressed by Wiener[15] over thirty years ago. This work was applied much later to ship hydrodynamics by such authors as Vassilopulos[16], Tick[17], and Hasselmann.[18]

The subsequent discussion of the theory of the Volterra series[19] to second order follows a brief presentation by Neal.[10] The Volterra series represents a causal physical system. This power series was used as a basis for the mathematical model for generating the slowly varying, second-order yaw moment and slowly varying, second-order sway-force time series, acting on the ship hull due to an oblique irregular wave in the UNREP simulation (see equations (1) for maneuvering equations).

THEORY

The present application involves the hypothesis that the sway force and yaw moment acting on a ship hull in oblique irregular waves can be represented by an infinite functional power series (the nonlinear system is assumed time invariant and the kernels thus depend only on time differences).

$$Y(t) = \sum_{n=o}^{\infty} F^{(n)}(t, x) \tag{3}$$

where:

$$F^{(o)}(t, x) = h_o \text{ (a constant)}$$

and
$$F^{(n)}(t, x) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} h_n(\tau_1, \cdots, \tau_n)\, X(t-\tau_1) \cdots X(t-\tau_n)\, d\tau_1 \cdots d\tau_n, \quad n > o$$

$h_n(\tau_1, \cdots, \tau_n)$ = kernel function (for analytic purposes, symmetric kernels may be assumed without loss of generality).

$X(t)$ = excitation which may be deterministic or stochastic.

In application to physical problems the series is truncated after n terms to yield a functional polynominial. The response, Y(t) for a finite number of terms will be mathematically meaningful if the input X(t) is bounded

and the kernels are each absolutely integrable. In addition, for the series to converge as $n \to \infty$ it is necessary that the contribution from terms of order n approach zero as n approaches infinity. For mathematical details a more rigorous description can be found in earlier references.[10,16-18,20,21]

It must be assumed for this work, that the series converges (e.g., Ku and Wolf[22]). We shall limit our analysis of the sway force and yaw moment to include excitation effects only through second order ($n = 2$) where $X(t)$ in this case is the irregular wave free-surface elevation at a reference point. Equation (4) is the fundamental mathematical model and is called a truncated functional power series or functional polynomial. This quadratic series can be used to analyze wave force or moment excitations on the ship hull that are proportional to the wave amplitude or the wave amplitude squared (system is assumed time invariant).

$$
\begin{aligned}
Y(t) &= Y^{(o)}(t) + Y^{(1)}(t) + Y^{(2)}(t) \qquad (4)\\
&= h_o + \int_{-\infty}^{\infty} h_1 (t - t_1)\, X(t_1)\, dt_1 + \cdots \\
&\quad + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2 (t - t_1, t - t_2)\, X(t_1)\, X(t_2)\, dt_1\, dt_2 \\
&= h_o + \int_{-\infty}^{\infty} h_1 (\tau)\, X(t-\tau)\, d\tau \\
&\quad + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_2 (\tau_1, \tau_2)\, X(t-\tau_1)\, X(t-\tau_2)\, d\tau_1\, d\tau_2
\end{aligned}
$$

Tick[17] has called equation (4) a time-invariant quadratic system, since it includes both a first-order and second-order term.

For the sway force and yaw moment, h_o in the truncated series (equation (4)) was set equal to zero. The first-order term $Y^{(1)}(t)$, is the familiar convolution integral for linear, time-invariant systems and can be used to represent the first-order sway force or first-order yaw moment acting on the ship hull. The irregular first-order sway force (and moment) acting on the ship hull generally contain many high-frequency as well as low-frequency components, and are zero-mean process. These terms were not considered in this work because they were studied earlier[8,9] and determined not to cause a significant control problem under the conditions of the simulation. The primary objective of this phase of the work was to study the effects of the slowly varying, nonlinear sea-state excitations acting on the ship's hull on the automatic controller performance of each ship. In Phase II "manual control" in different first-order regular seas[8] was considered, and in Phase III[9] preliminary work using automatic control with first-order, linear irregular sea effects (sway force and yaw moment) were considered. In either case, under the conditions of the simulation, the first-order sea state effects

did not produce a significant control problem. The statement does not apply to low-frequency, high-amplitude swell. First-order sway force (and yaw moment) time series can be easily added to the maneuvering equations of motions in later work.

The second-order term $Y^{(2)}(t)$ with the second-order impulse response, $h_2(\tau_1, \tau_2)$, is the basic mathematical term that will be used to study the second-order force (and moment) wave excitations throughout this work. The second-order sway force (and yaw moment) each consist of two components; (1) the rapidly varying (high-frequency), second-order component; and, (2) the slowly varying, second-order component. The rapidly varying sway force (and yaw moment) are a zero-mean process and are neglected in this work. It is the slowly varying component of the sway force (and yaw moment) each containing a (D. C. offset) non-zero mean, which cause the ship's large surface excursions, that must be controlled by the rudder.

SLOWLY VARYING, SECOND-ORDER WAVE EXCITATIONS

The Gaussian stochastic integral representation[10] will be used to represent the irregular sea.

$$X(t) = \int_0^\infty \cos\,(\omega t - \varepsilon(\omega)\,\sqrt{2S_x(\omega)d\omega} \tag{5}$$

$$\cong \lim_{\substack{\omega_n \to \infty \\ \delta\omega \to 0}} \sum \cos\left[\omega_n t - \varepsilon(\omega_n)\right]\left[2S_x(\omega_n)\ \delta\omega\right]^{1/2}$$

where the radial $\left[2S_x(\omega)\ \delta\omega\right]^{1/2}$ represents the amplitude of each harmonic wave in the sum.

Where:

ω = radian frequency

$S_x(\omega)$ = one-sided wave energy spectrum for irregular sea state (Pierson-Moskowitz wave energy spectrum)

$\varepsilon(\omega)$ = uniformly distributed random phase angles from 0 to 2π.

Substituting $X(t)$, equation (5), into the second-order term $Y^{(2)}(t)$ (equation (4)), results in the following expression:

$$Y^{(2)}(t) = \text{RAPIDLY VARYING, SECOND-ORDER TERM} + \text{SLOWLY VARYING, SECOND-ORDER TERM} \tag{6}$$

$$Y^{(2)}(t) = \int_0^\infty \int_0^\infty \cos\left[(\omega_1 + \omega_2)t - (\varepsilon(\omega_1) + \varepsilon(\omega_2)) + \phi(\omega_1, \omega_2)\right] \times \sqrt{|H(\omega_1, \omega_2)|^2 S_x(\omega_1) S_x(\omega_2)}\, d\omega_1\, d\omega_2$$

$$+ \int_0^\infty \int_0^\infty \cos\left[(\omega_1 - \omega_2)t - (\varepsilon(\omega_1) - \varepsilon(\omega_2)) + \phi(\omega_1, -\omega_2)\right] \times \sqrt{|H(\omega_1, -\omega_2)|^2 S_x(\omega_1) S_x(\omega_2)}\, d\omega_1\, d\omega_2$$

where $H(\omega_1, \omega_2)$ is called the second-order transfer function and is defined as

$$H(\omega_1, \omega_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(\tau_1, \tau_2) e^{-i\left[\omega_1 \tau_1, + \omega_2 \tau_2\right]} d\tau_1\, d\tau_2. \tag{7}$$

The transfer function can be written in terms of the amplitude and phase components as

$$H(\omega_1, \omega_2) = |H(\omega_1, \omega_2)|\, e^{i\phi(\omega_1, \omega_2)}. \tag{8}$$

For details of the derivation, see Neal[10].

The first term in equation (6) can be used to represent the contribution of the wave frequency pair sums to the second-order wave forces (or moment) excitation. The second term in equation (6) will be used to represent the contribution of wave frequency pair sum differences to the second-order wave force (or moment excitations). Following past investigations, we shall call the first term the rapidly varying, second-order term and the second term the slowly varying, second-order term.

In summary, the slowly varying, second-order term in equation (6) will be used to generate both the slowly varying, second-order sway force and the slowly varying, second-order yaw moment for the UNREP simulation. The input required for producing the slowly varying excitations on the ship hull is as follows:

- The sea state wave energy spectrum $S_x(\omega)$, (Pierson-Moskowitz).
- The transfer functions associated with the slowly varying, second-order sway force (and yaw moment).

Since the information for the transfer function is generally not available, the estimation of the transfer functions will be considered next.

ESTIMATION OF THE TRANSFER FUNCTIONS

Little knowledge of the "second-order transfer function" is available for hydrodynamic systems in waves. In 1970, Lee[23] calculated the second-order transfer function for forced oscillations of two-dimensional cylinders floating on the free surface. A general practical theory does not appear available at this time for determining the general second-order transfer function for an arbitrary ship wave system.

A very general approach using cross bi-spectral analysis for determination of the second-order transfer function $H(\omega_1, \omega_2)$ for ship problems has been discussed by Tick[17] and Hasselmann[18]. Tick's expression for the transfer function is obtained in terms of physically realizable spectra as (see Neal[10] for a detailed discussion of the derivation):

$$H(\omega_1, \omega_2) = \frac{S_{xxy}(\omega_1, \omega_2)}{2S_x(\omega_1)S_x(\omega_2)} \tag{9}$$

where:

$S_{xxy}(\omega_1, \omega_2)$ = physically realizable cross-bi-spectral density function

and $S_x(\omega)$ = one-sided spectral density function

The transfer function must be symmetric and thus satisfy the relationship:

$$H(\omega_1, \omega_2) = H(\omega_2, \omega_1). \tag{10}$$

Therefore, the cross-bi-spectrum analytic technique cannot be used directly to determine nonsymmetric transfer functions.

This method has the drawback that expensive experimental records from model testing must be taken. From these records, a third-order moment $R_{xxy}(\tau_1, \tau_2)$ must be determined[10], and complex mathematical manipulation and computer techniques must be used to determine the transfer function. This method was not used in this work primarily because of the cost.

This synthesis, however, deals with the slowly varying nature of the important nonlinear forces (or moments) which can be estimated by an approximate method developed by Newman[11]. This method disregards the rapidly varying, second-order forces (and moments) which are not considered to be important in the maneuvering UNREP problem being studied here.

Newman[11] approximates the slowly varying transfer function $H(\omega_n,-\omega_m)$, (which is real for symmetric transfer functions) by approximating the function in the bi-frequency plane by its diagonal value $H(\omega_n,-\omega_n)$. These diagonal values must be obtained by model testing involving monochromatic (regular) waves or theoretical calculations involving complex hydrodynamic potential calculations. Since these data are sometimes found in the literature, model experiments can sometimes be avoided. In general, however, the error resulting from this approximation cannot rigorously be determined. Therefore, for practical engineering purposes, as in the work here, this approximation offers the only possibility for analysis of the slowly varying forces (or moments). For a detailed discussion of this approximation, the reader should consult Newman's paper where he considers the discrete analog of equation (6).

In the work performed here, the transfer functions associated with the slowly varying sway force and the slowly varying yaw moment were estimated by Newman's approximation. Thus, a curve of the mean sway force (or yaw moment) developed on a ship model at a particular speed in a specified oblique regular wave divided by the wave amplitude, squared, versus wave encounter frequency were used for the estimated sway (or yaw) transfer function. These curves were determined from model test data taken by Chey[12] at the Stevens Institute of Technology for a Series 60 (C_b = 0.60) restrained ship model proceeding at 15 knots into oblique regular waves (ship-to-wave angle $\chi = 150^o$ (2.168 rad), see figure 2) at different regular wave encounter frequencies ω_e. The Series 60 model is very similar to the Mariner Study Ship used in the UNREP simulation. See Appendix B for model particulars, model test information, curves, and detailed discussion of the limitations of the data for this work.

The experimental results from a restrained ship model were used because it was the only experimental data available to the authors at the time of the work. Lalangas[24] reports that for a ship in beam seas at zero speed, the drift force on a model which is free to move is different from the drift force on a restrained hull. Discussions of the drift force and moment on a ship in waves can be found in other references.[25,26] Thus, it appears that it would be more realistic for this work to have data from partially restrained model testing. There is a definite need for more realistic sway and yaw data so that better transfer functions can be estimated for simulation purposes. With more realistic transfer functions, the validity of the Newman approximation could be determined with greater accuracy. Chey's data were also rather limited as to the number of available experimental points for plotting the estimated transfer functions.

The limitations in the transfer functions used in this work, however, probably do not have a large effect on the performance of the automatic controller during the simulation which is of primary concern in this work. Simulation results discussed later show that the controller is relatively insensitive (number of orders of magnitude) to large changes in the slowly varying sway force (and yaw moment) excitations. This point will be discussed in some detail later in the report.

SWAY FORCE AND YAW MOMENT TIME SERIES

Digital computer simulation programs developed by Neal by using equation (11) as the basis for the mathematical model, were used to generate the time series of the slowly varying, second-order sway force and the slowly varying, second-order yaw moment acting on the Mariner Study Ship proceeding at 15 knots into oblique irregular waves ($\chi = 150^o$ (2.618 rad))

$$Y_2^{(2)}(t) \cong \int_0^\infty \int_0^\infty \cos\left[(\omega_1 - \omega_2)t - (\varepsilon(\omega_1) - \varepsilon(\omega_2)) + \phi(\omega_1, -\omega_2)\right] \times \sqrt{|H(\omega_1, -\omega_1)|^2 S_X(\omega_1) S_X(\omega_2)\ d\omega_1}\ d\omega_2 \qquad (11)$$

where H $(\omega_1, -\omega_1)$ is assumed to approximately equal $H(\omega_1, -\omega_2)$ which is Newman's approximation. In the computer calculation ω_1 and ω_2 are the encounter frequencies.

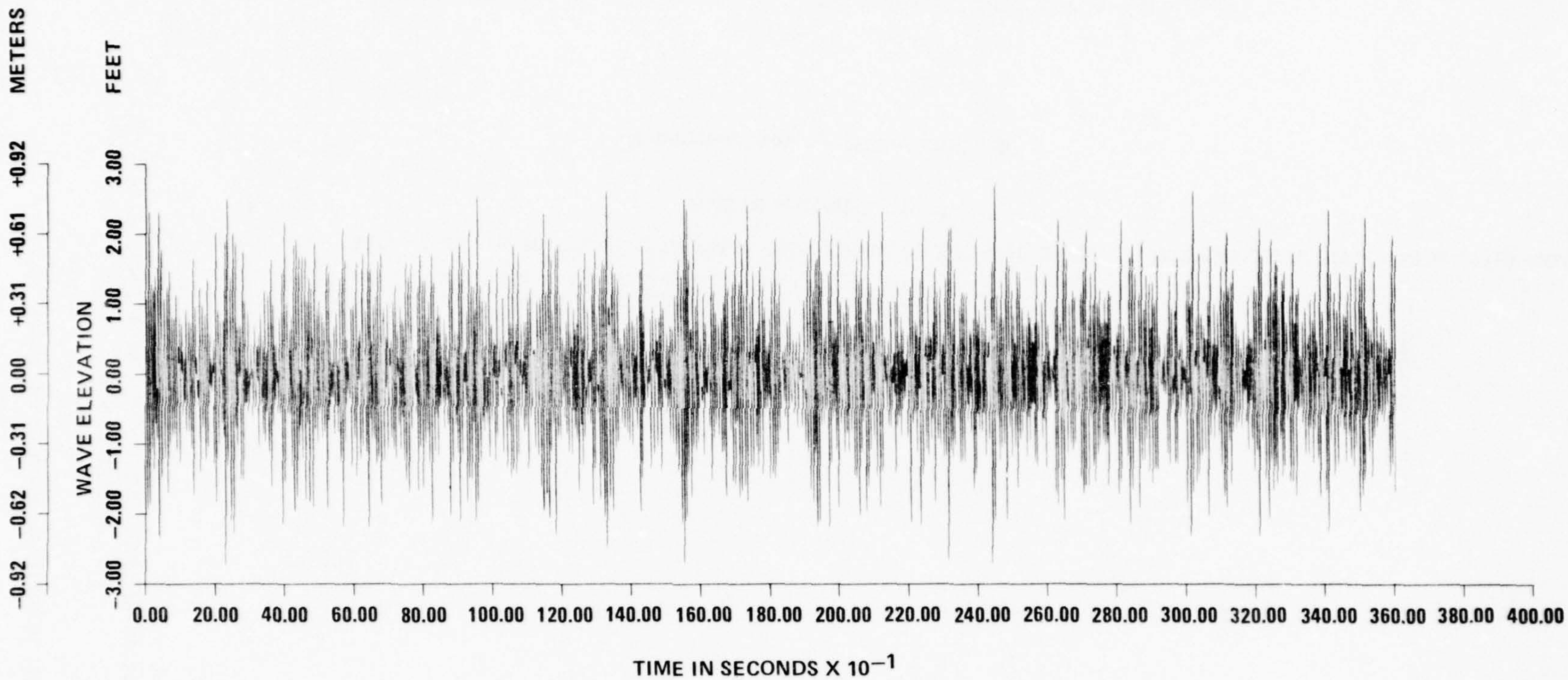
The computer input required to generate the time series consists of a wave energy spectrum $S_x(\omega)$, and the approximation to the transfer function associated with the slowly varying sway force (or moment).

It is assumed that the oblique irregular seaway in the UNREP simulation is unidirectional and long crested. The seaway is statistically represented in this work by a Pierson-Moskowitz wave energy spectrum representing a sea state 4 on the Beaufort Scale (approximately 4-feet significant wave height). The wave height time series that corresponds to the Pierson-Moskowitz wave energy spectrum[27,28] is shown in figure 5. A digital approximation to the random phase model (see equation (5)) was used to generate the wave surfaces with Gaussian distribution properties.

In Appendix B, Chey's data that were used for determining the estimated nonlinear transfer functions associated with the sway force and yaw moment excitation are reported.

The digital computer generated slowly varying, hydrodynamic sway force versus time, and the slowly varying hydrodynamic yaw moment versus time acting on the Mariner Study Ship at 15 knots in a 30^o (.524 rad) bow irregular sea (approximate significant wave height of 4 feet) are presented in figures 6 and 7, respectively. Both time series were recorded on computer cards at a sampling rate of 0.5 sec for UNREP hybrid computer simulations.

The objective here was to use Newman's approximation to estimate the slowly varying, second-order sway force (or moment excitations) for any given time history of the wave elevation. The conditional results show that the simulated sway force and yaw moment time series (figures 6 and 7) appear generally to have the correct statistics. Both have a D.C. offset



*Sea state 4 on Beaufort scale (approximately significant wave height of 4 feet)

Figure 5
Stationary Seaway Represented by Wave Height Time Series

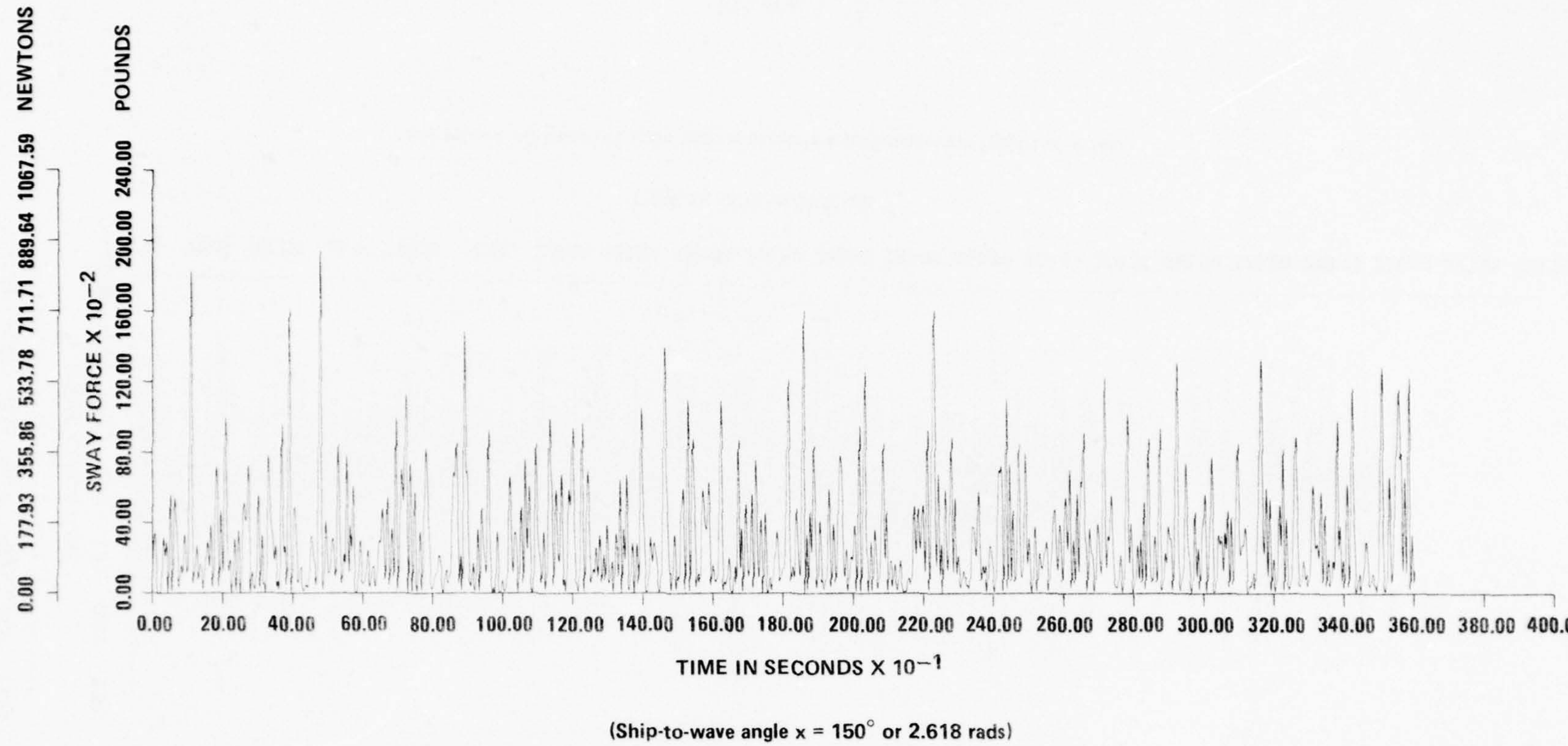


Figure 6
Hydrodynamic Slowly Varying, Second-Order Sway Force Versus Time for Mariner Study Ship at 15 Knots in Oblique Irregular Waves ($\chi = 150^o$)

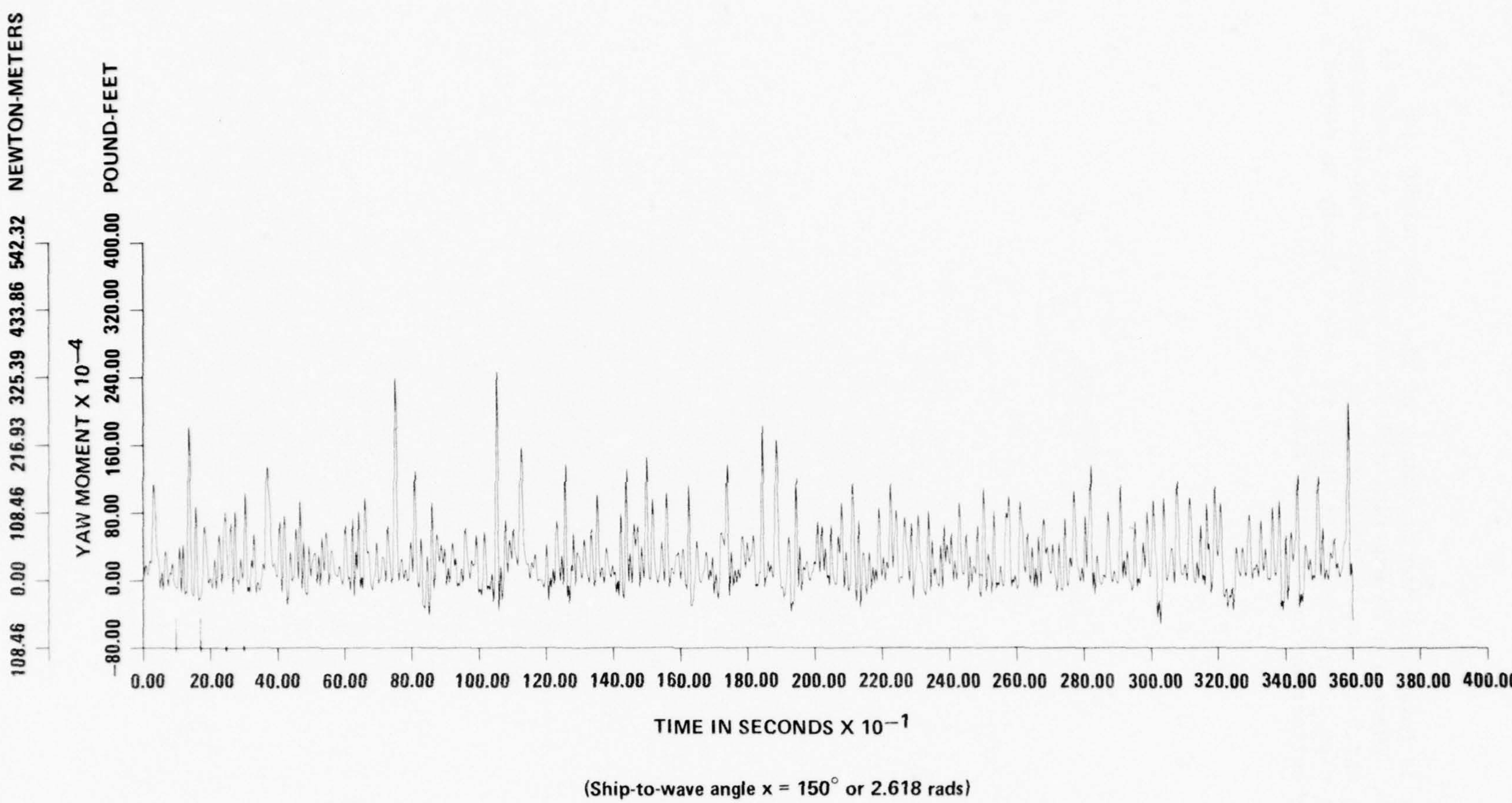


Figure 7
Hydrodynamic Slowly Varying, Second-Order Yaw Moment Versus
Time for Mariner Study Ship at 15 Knots
in Oblique Irregular Waves ($\chi = 150^{o}$)

and the frequency is lower than the frequency of the wave height time series (figure 5). There are no experimental data available, or known to the authors, with which to compare these results. However, the provisional simulated results seem to indicate that there is some validity in Newman's approximation for estimating the transfer functions.

THE AUTOMATIC CONTROLLER

The automatic feedback control algorithms required for this phase of the project were primarily developed in the Phase III work (see Alvestad[9]). During UNREP maneuvers at sea, the leading ship is charged with maintaining a constant heading while the tracking ship is responsible for maintaining a constant separation distance. In the hybrid computer simulation, the algorithms for the two ships are adjusted to reflect their different control functions. The basic control algorithm is as follows (see figure 8):

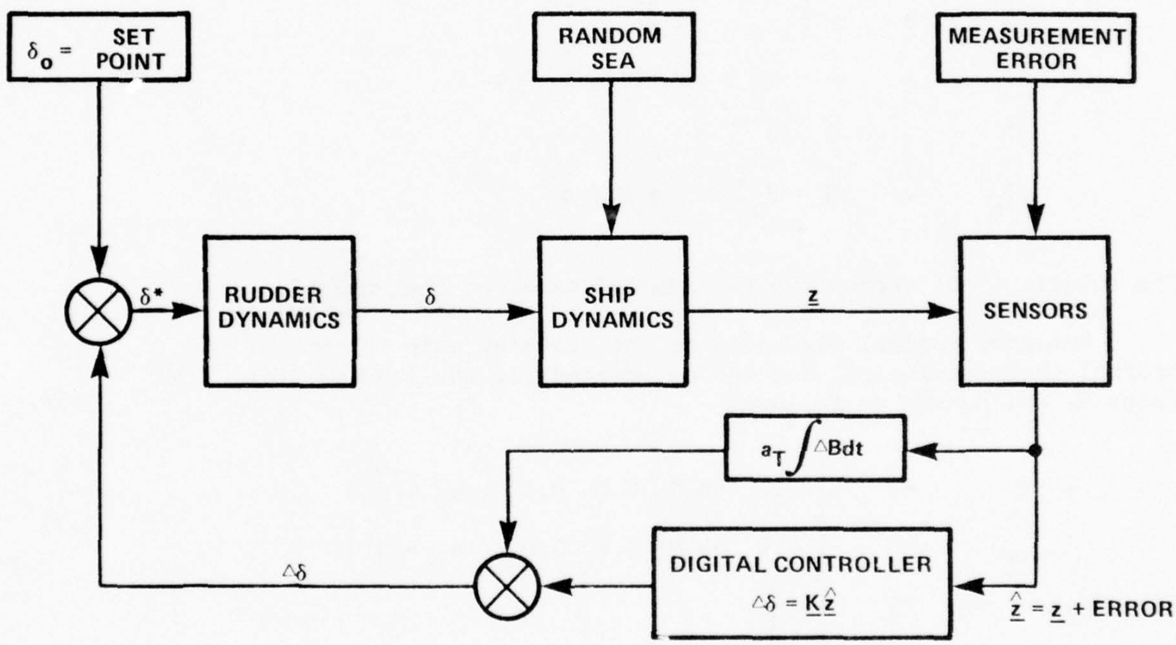


Figure 8
Automatic Control Configuration

The main control law for the digital automatic controller is as follows:

$$\delta^* = \delta_o + \Delta\delta$$
$$\Delta\delta = \underline{K_1}\Delta\psi + \underline{K_2}\dot{\psi} + \underline{K_3}\Delta B + \underline{K_4}\dot{B} + a_T \int \Delta B dt \qquad (12)$$

where:

δ_o	=	nominal rudder angle
$\Delta\delta$	=	rudder perturbations about δ_o (output from digital controller)
$\underline{K_i}$	=	feedback gain constants (i = 1, 2, 3, 4)
a_T	=	gain constant in integral feedback loop
$\Delta\psi$	=	$\psi - \psi_o$
$\Delta\dot{\psi}$	=	$\dot{\psi} - \dot{\psi}_o = \dot{\psi}$, since $\dot{\psi}_o = o$
ΔB	=	$B - B_o$
$\Delta\dot{B}$	=	$\dot{B} - \dot{B}_o$, since $\dot{B}_o = o$

The subscript 0 represents the nominal value of the variable.

Integral control was added to the tracking ship to improve the control characteristics, but was not needed for the leading ship. The gains $\underline{K_L}$ and $\underline{K_T}$ are as follows:

$$\underline{K_L} = \begin{bmatrix} 20.0 & 40.0 & 0.0 & 0.0 \end{bmatrix} ; \; a_T = 0.0$$
$$\underline{K_T} = \begin{bmatrix} 10.0 & 35.0 & 0.6 & 3.0 \end{bmatrix} ; \; a_T = 0.03 \qquad (13)$$
$$\text{and } \hat{\underline{z}} = \begin{bmatrix} \Delta\psi \\ \dot{\psi} \\ \Delta B \\ \dot{B} \end{bmatrix}$$

where L and T represent leading and tracking ship, respectively. It must be kept in mind that all motion variables are actually perturbation variables about the nominal condition. Thus, ΔB represents the actual distance minus the desired distance.

For passing maneuvers, the tracking ship feedback vector was changed to

$$\underline{K_T} = \begin{bmatrix} 20.0 & 40.0 & 3.0 & 14.0 \end{bmatrix} \tag{14}$$

to improve the steady state error characteristics.

For detailed discussions concerning the automatic controllers, the reader should consult the Phase III UNREP report[9].

SIMULATION RESULTS

The simulation results for the irregular sea condition are shown in figures 9 through 16 where both ships' speeds are approximately 15 knots. The interaction data limits the range in side-to-side separation distance from 50 (15.24 m) to 150 (45.72 m) feet. Allowable rudder commands are limited to ±20 degrees. Each of the two ships has a separate automatic controller. On the leading ship, the controller maintains a constant heading, while on the tracking ship the controller's function is to maintain the lateral separation distance at the desired value (100 feet). The controllers are not directly coupled. The maneuvers simulated include station keeping, lateral station changing, and the approach and breakaway of the tracking ship. In all subsequent figures, the subscripts L and T denote the leading and tracking ships, respectively.

Figures 9 through 11 show station keeping at a longitudinal separation distance A of A = 0, +550 (+167.64 m) and -550 (-167.64 m) feet, respectively. The slowly varying sway force Y_S (χ) and slowly varying yaw moment N_S (χ) induced by the irregular sea on the ship hull are stored on the digital portion of the hybrid simulation as 20-minute time series which are inputed to the ships' dynamic model as forcing functions at half-second intervals. These components are shown on channels 7 and 8 of the figures. The nonlinear interaction forces are also inputed to the ships' dynamic model, but are not shown on the graph recordings. Figures 9 through 11 show that the automatic controller on each ship performs well in the station keeping mode under the conditions of the simulation (approximately 4 on Beaufort scale).

Controller performance for station changing commands is shown in figures 12 and 13. Commands were made to change separation distance B from 100 feet (30.48 m) to 125 feet (38.10 m). In figure 12 the command is a ten-second ramp while in figure 13 the command is a step input. The controller increases the separation distance to the desired value in both cases. However, the step command (figure 13) creates undesirable rudder transients and should therefore be avoided.

The time series components Y_S (χ) and N_S (χ) acting on the ship hull are caused by a fully developed, wind-driven (approximately 11-16 knots) sea state with a significant wave height of approximately 4 feet (4 on Beaufort scale). To simulate a more severe sea condition, the component force and moment magnitudes were increased by a factor of 3. The resulting simulated maneuver is shown in figure 14. Adequate control is maintained, although perturbations on several variables are noticeable.

Figure 15 shows a complete passing maneuver where the longitudinal separation A changes from -550 feet (-167.64 m) to +550 feet (+167.64 m) in approximately 9 minutes. A maximum change of about 6 feet (1.83 m) in the

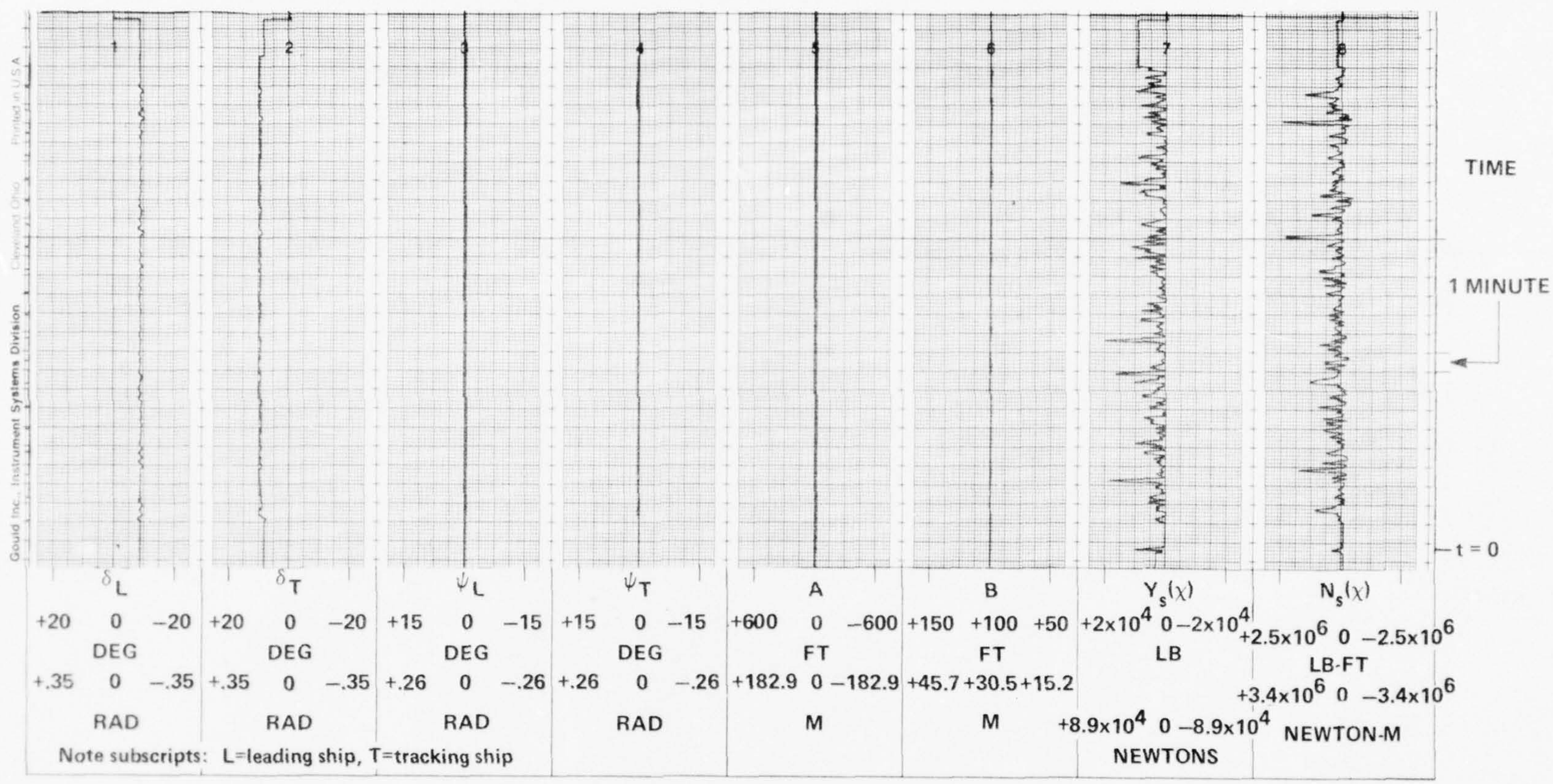


Figure 9
Station Keeping with Longitudinal Separation of A=0 Feet

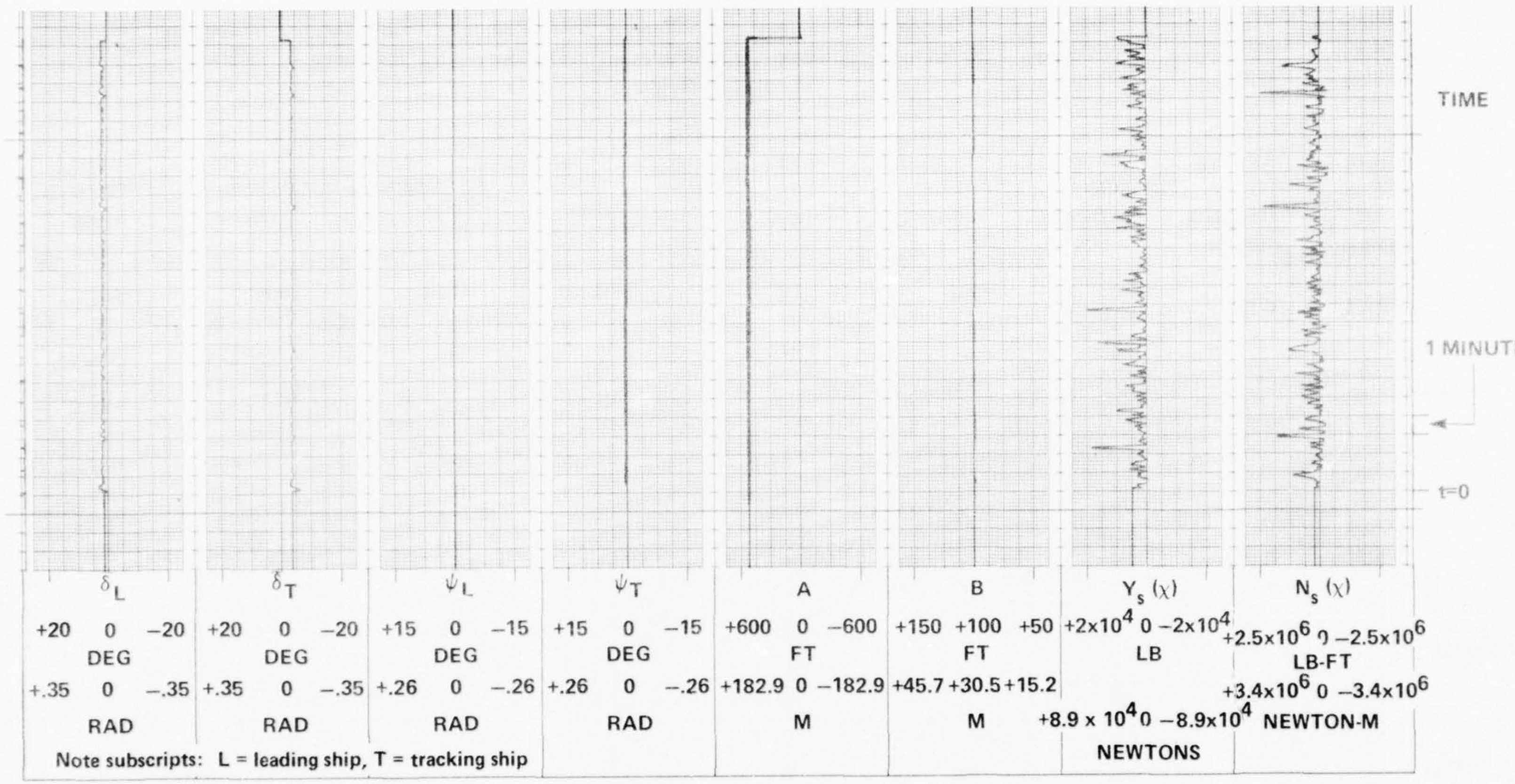


Figure 10
Station Keeping with Longitudinal Separation of A=+550 Feet

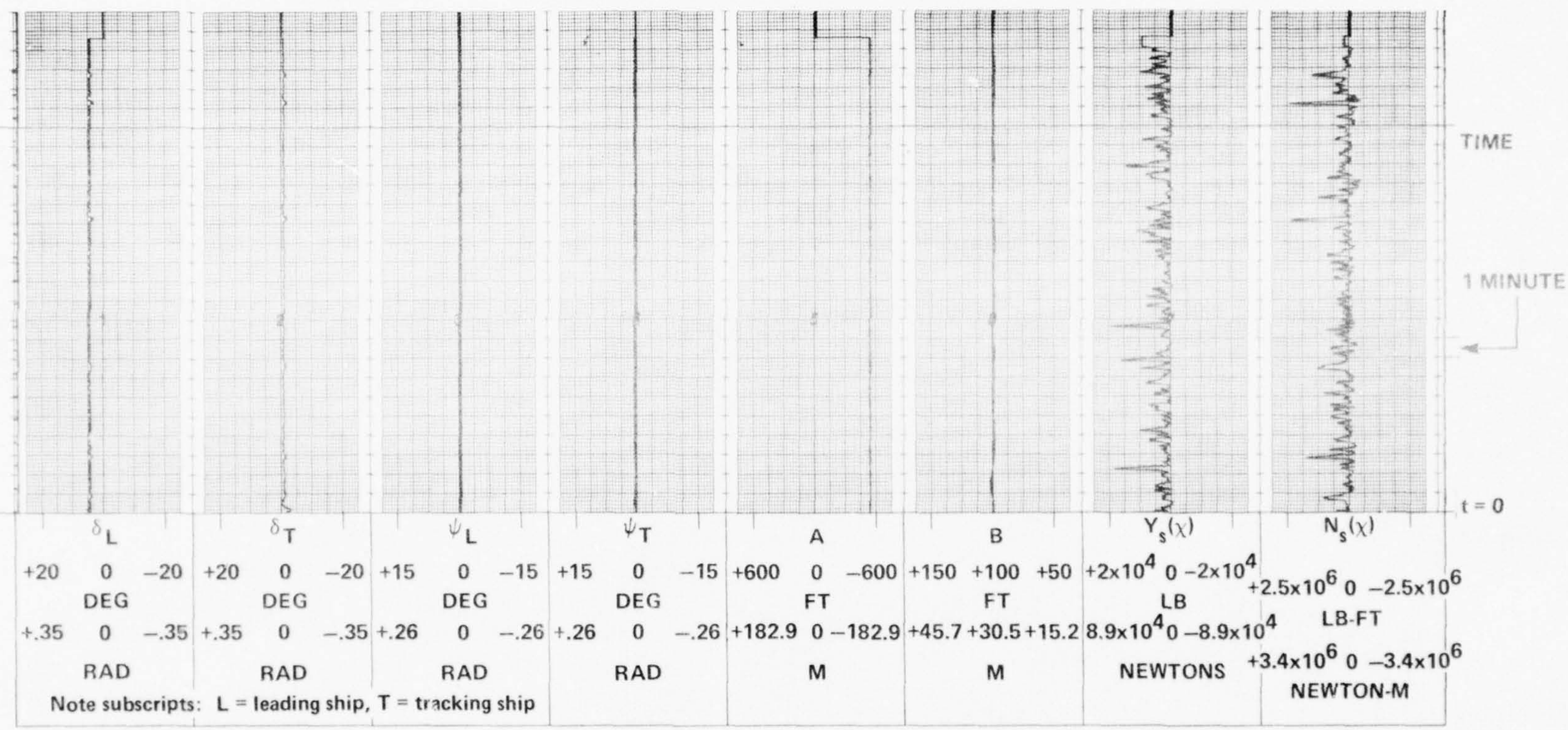


Figure 11
Station Keeping with Longitudinal Separation of A=-550 Feet

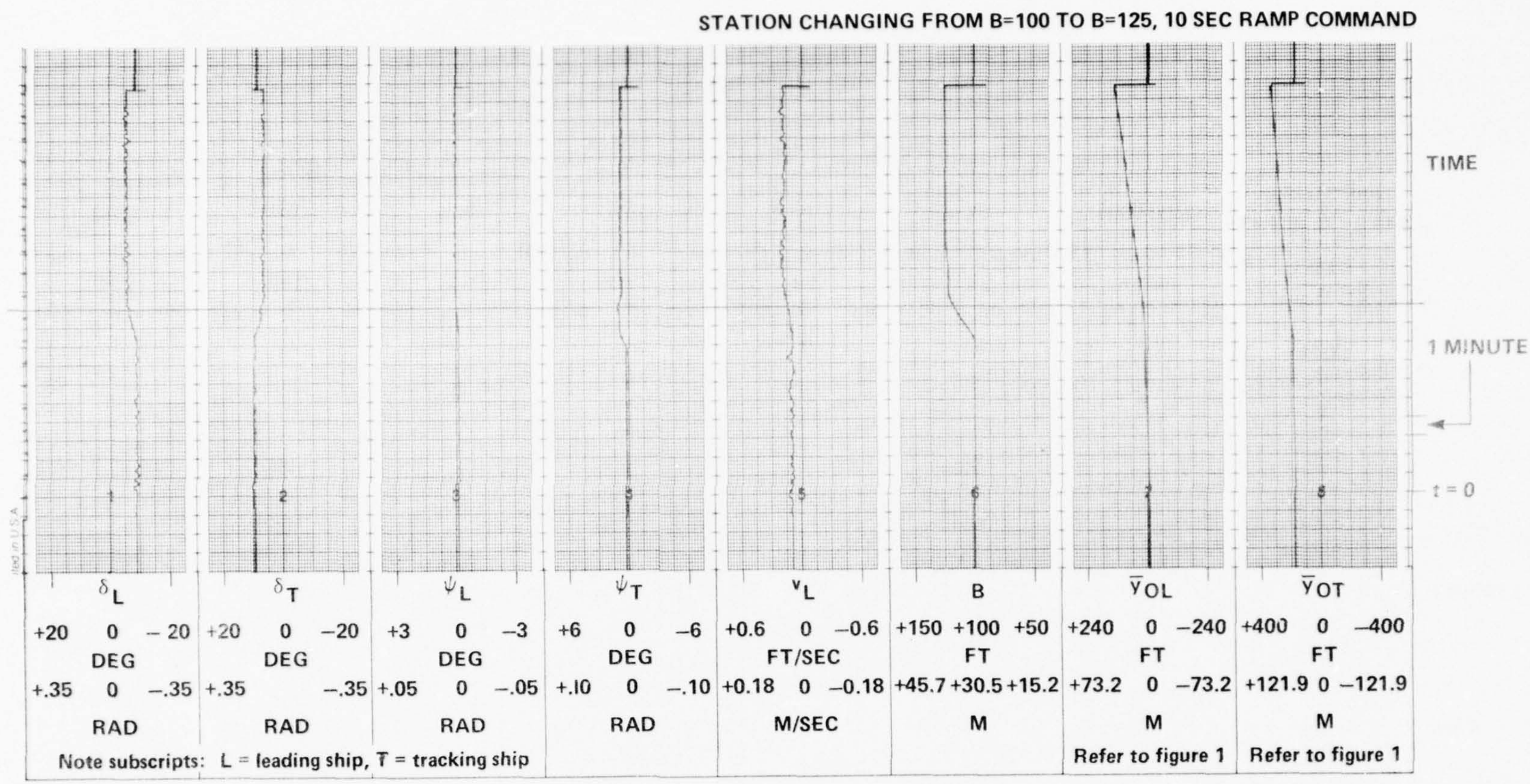


Figure 12

Station Keeping (A = 0) with Change in Separation Distance (10 sec. Ramp)

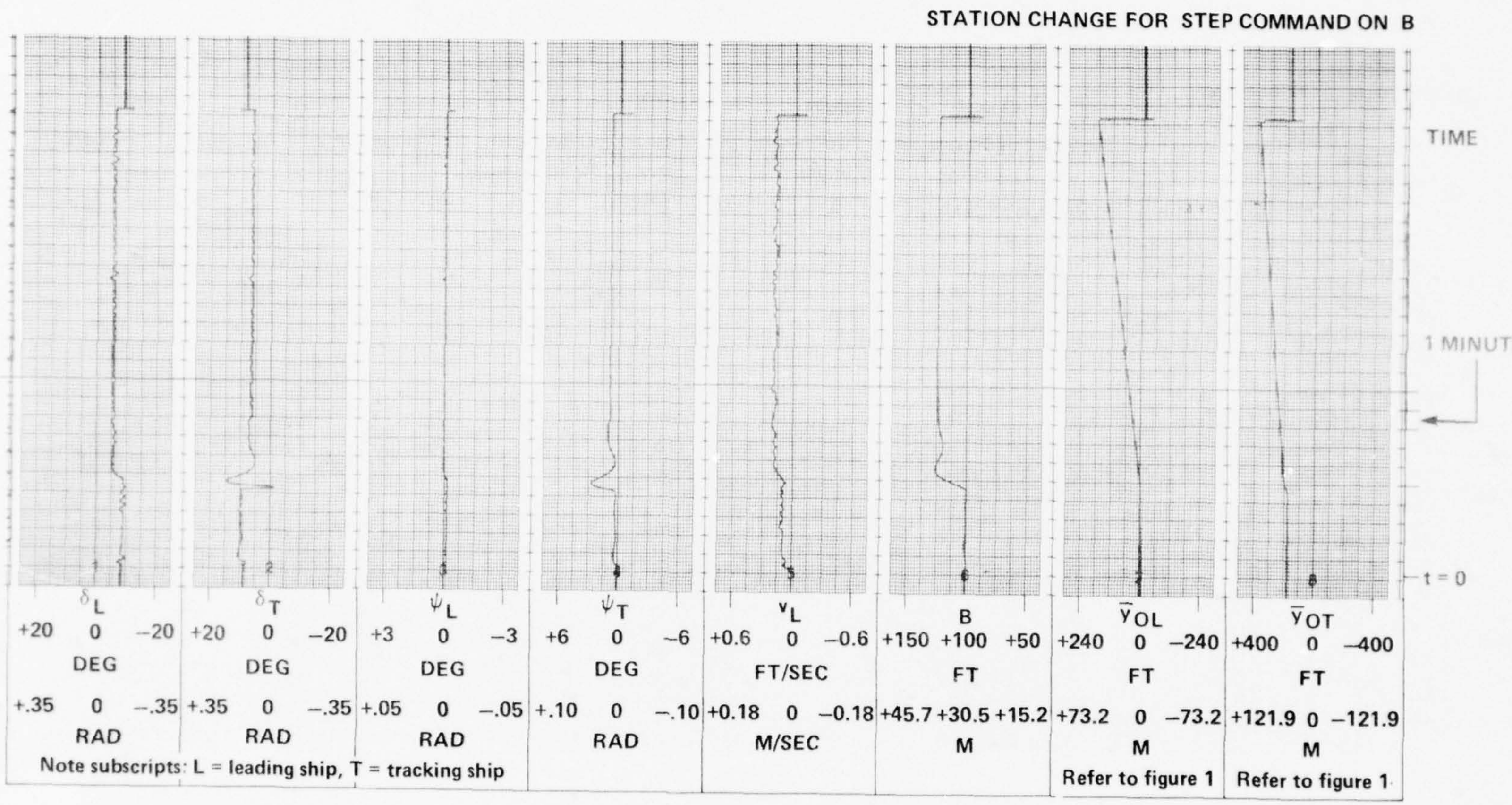


Figure 13
Station Keeping (A = 0) with Change in Separation Distance (Step Input)

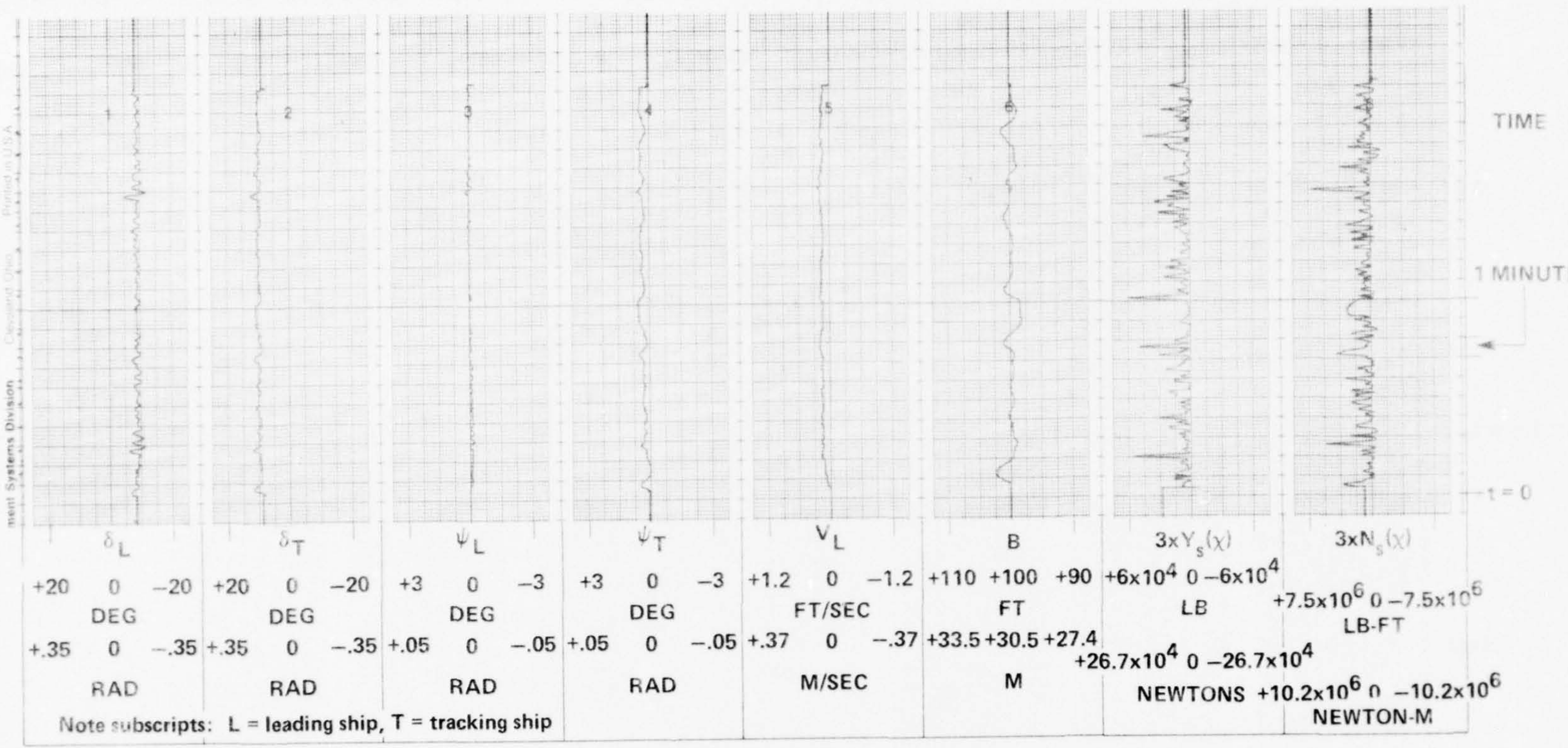


Figure 14
Station Keeping (A=0) in Higher Irregular Sea

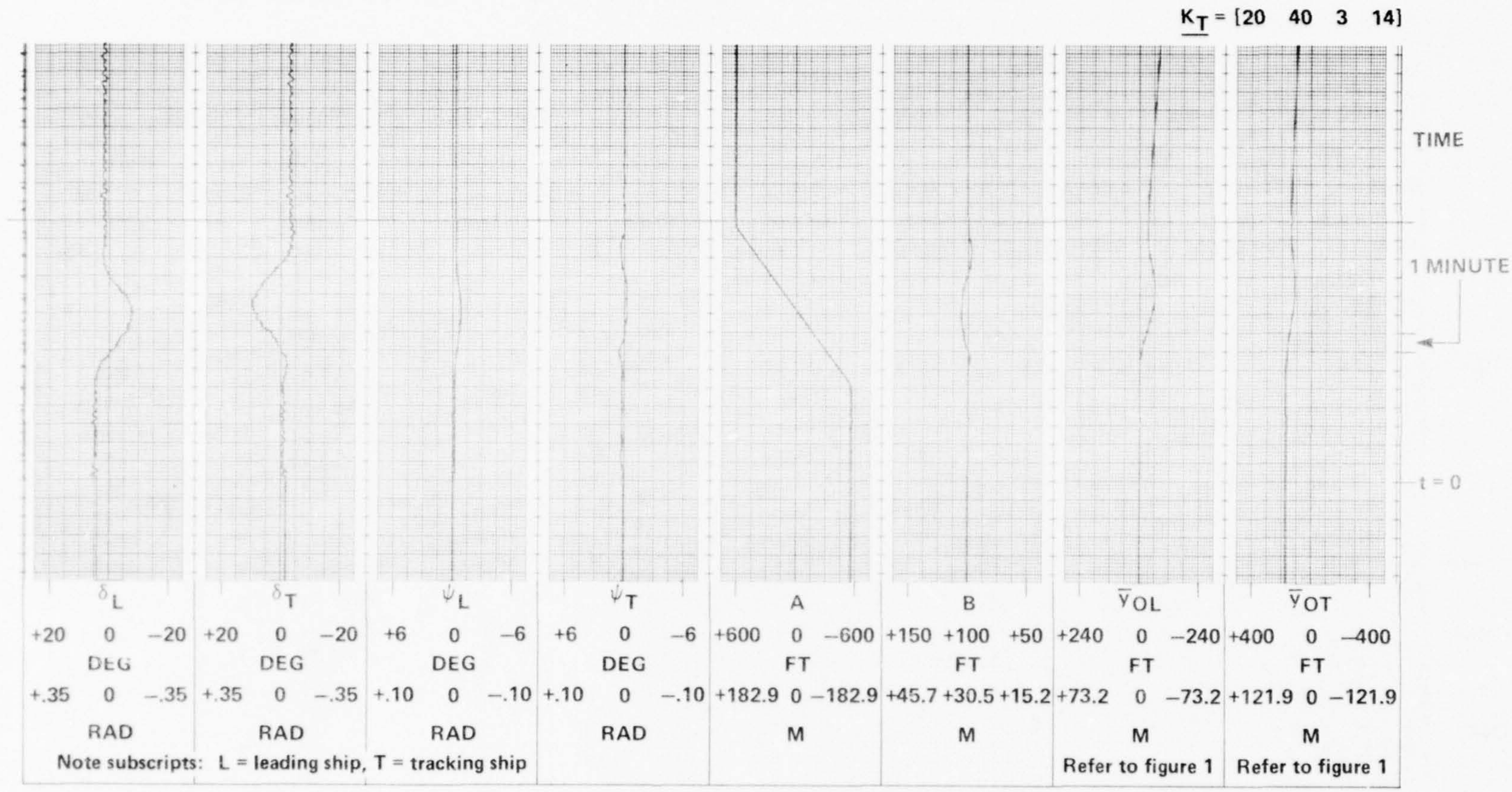


Figure 15
Passing Maneuver Where A Changes from -550 ft to +550 ft

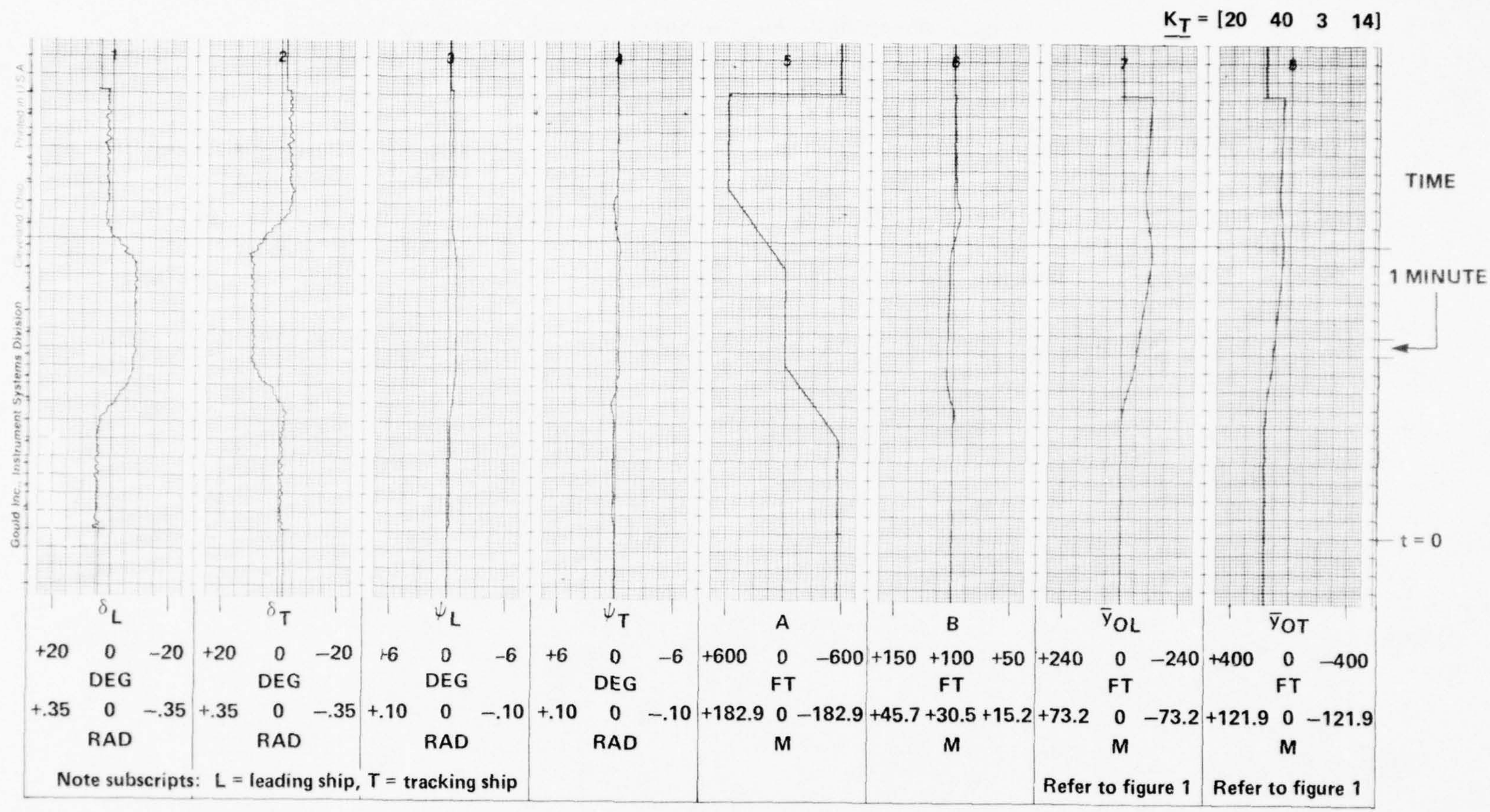


Figure 16
Passing Maneuver Where A Changes from -550 ft to +550 ft with a Hold at Midships

lateral separation distance is experienced during the maneuver. Sideslip (lateral drift) reaches approximately 90 feet (27.43 m) during the 20-minute run. Since UNREP is generally performed in open water, lateral drift does not present a problem. Even so, lateral drift can be counteracted by adequate course changes on the leading ship.

Figure 16 is the same maneuver with a hold in the longitudinal separation at A = 0 feet to simulate the actual replenishment operation. The maximum change in the lateral separation distance is again approximately 6 feet (1.83 m).

The simulation results imply that the automatic control device performances are not adversely affected by the slowly varying force and slowly varying moment resulting from the nonlinear frequency interactions of the waves. Accordingly, an increase of three times the slowly varying sway force and slowly varying yaw moment does not appreciably affect the lateral separation distance between the two ships. This may, in turn, suggest that an appreciable error in the evaluation of the nonlinear sway force and moment can be tolerated on the simulation of UNREP operation. However, unless the simulation results are validated against full-scale UNREP sea trials or model testing data using automatic control, these results should only be considered as provisional.

Work is needed to add important nonlinear maneuvering coefficients to the UNREP maneuvering equations. The first-order sway force (and yaw moment), and higher sea states should also be incorporated in the simulation. Also, more reliable data are needed to estimate the transfer functions associated with the nonlinear sway force and yaw moment so that these hydrodynamic coefficients can be evaluated accurately. It should also be remembered at this point, that the UNREP mathematical model represents the nonlinear response of the system to nonlinear sea state excitations.

SENSITIVITY ANALYSIS

A preliminary analysis of controller sensitivity to errors in measurement of the feedback variables was performed in the Phase III work.[9] However, in the current work, the controller design has been modified with the addition of integral feedback, and some approximate nonlinear irregular sea state excitations. Therefore, sensitivity is again considered, with the following modifications:

- Since the frequency response cut-off point for the control loop is approximately 1 Hz, only low-frequency drift and D.C. errors are important.

- Errors in separation distance are measured in response to a step error (D.C.) in each feedback variable. This is considered the worst case.

- Recommended measurement accuracies are specified in absolute units.

Since the controller contains an integral feedback loop (see figure 9) errors in the separation distance B caused by errors in the measurement of the feedback variables will be slewed to zero after an initial transient. This does not hold, however, if the measurement error is in the value of B itself, since an error in B is equivalent to a change in the desired separation distance. Thus, a one-foot error in the measurement of B will result in a one-foot error in the actual separation distance. The absolute initial controller error due to step errors in the feedback variables is presented in Table 2. In each case, the variable error is approximately 5% of the expected maximum value. The expected maximum values are as follows:

- ψ_{max} = 15 deg (.262 rad)
- $\dot{\psi}_{max}$ = 2 deg/sec (.035 rad/sec)
- B_{max} = 150 feet (45.72 m)
- $\dot{B}_{max}$ = 10 feet/sec (1.82 m/sec)

TABLE 2 CONTROL-VARIABLE ERRORS				
ERROR VARIABLE	ABSOLUTE VARIABLE ERROR (5%)		LATERAL SEPARATION DISTANCE ERROR	
ψ_T	.75 deg	(.013 rad)	10.0 ft	(3.05 m)
$\dot{\psi}_T$	.10 deg/sec	(.002 rad/sec)	3.5 ft	(1.07 m)
B	7.50 feet	(2.29 m)	7.5 ft	(2.29 m)
$\dot{B}$	.50 feet/sec	(.51 m/sec)	1.0 ft	(.30 m)
ψ_L	.75 deg	(.013 rad)	10.0 ft	(3.05 m)
$\dot{\psi}_L$	.10 deg/sec	(.002 rad/sec)	3.5 ft	(1.07 m)

Errors in the maximum value of the control variables much in excess of 5% tend to cause the automatic controller to become unstable. The controller functions well with errors up to 5% in the maximum variable value.

Since the measurement of heading (ψ) and heading rate ($\dot{\psi}$) by current techniques seldom leads to step errors, the error in separation distance caused by errors in these variables will be less than that shown in Table 2. However, depending on the measurement device, electronic sensor or manual, errors in B and $\dot{B}$ may be discrete. The recommended maximum error criterion for measurement of the feedback variables under the conditions of the simulation is as follows:

ψ_T = .5 deg (.009 rad)

$\dot{\psi}_T$ = .1 deg/sec (.002 rad/sec)

B = 4.0 feet (1.220 m)

$\dot{B}$ = .5 feet/sec (.150 m/sec)

ψ_L = .5 deg (.009 rad)

$\dot{\psi}_L$ = .1 deg/sec (.002 rad/sec)

It should be realized that these results are for moderate seas (4 on Beaufort Scale) and that the UNREP mathematical model has limitations. Therefore, these results are provisional and may not hold for high seas. However, the good performance of the automatic controller on each ship under the conditions of the UNREP simulation are demonstrated since, the controllers do not appear to be sensitive to errors in sensor measurement.

DISCUSSION AND CONCLUSIONS

Phases I through III included the beginning development of a hybrid computer underway replenishment maneuvering simulation for two Mariner ships. Simulation of UNREP for two ships in calm and regular seas using both "manual" and automatic control were performed in the three phases. This work revealed that the control variables required for display include heading angle, heading angle rate, longitudinal separation distance, lateral separation distance, lateral separation distance rate, propeller shaft revolutions, and rudder angle. The relatively high-frequency, first-order, sway force (and yaw moment) were determined not to be a control problem under the conditions of the simulation.

In the Phase IV work presented here, the emphasis was placed on performing a sensitivity analysis of the maneuvering control variables during UNREP simulations. Some approximate nonlinear sea-state excitations acting on the ships' hulls due to a specific irregular sea were added to the simulation model. Nonlinear sea state excitations were only considered in this work. The Volterra Series formulation was used as the basis for the mathematical model to generate the slowly varying, second-order sway force (and moment). The forces and moments were represented during UNREP simulations by time series. Newman's approximation was used to estimate the transfer functions associated with the slowly varying sway force and slowly varying moment. The first-order sway force (and yaw) could be incorporated in the UNREP mathematical model in future work.

The approximate nonlinear sea-state excitations acting on the ships' hulls together with an automatic controller on each ship were incorporated into the UNREP simulation and used for control variable sensitivity studies. The automatic controllers were developed in earlier work. The sensitivity analysis indicated that sensor noise and measurement errors of 3% to 5%[9] in the control variables should be acceptable for a ship separation monitoring system under the conditions of the simulation (4 and 5 on the Beaufort Scale, moderate sea states). The good ship control performance of automatic control during UNREP simulations were demonstrated. Thus, automatic control should be considered for collision avoidance during UNREP.

These results may be provisional, however, since there are some limitations in the UNREP simulation mathematical model. First, nonlinear terms containing the nonlinear maneuvering coefficients were not used in the maneuvering equations that form the basis for the mathematical model in the UNREP simulation. Second, the data used for estimating the transfer functions associated with the slowly varying sway force (and yaw moment) were limited in scope and accuracy. Also, the validity of Newman's approximation must be determined. Third, it is assumed that the automatic controller is generally not required to compensate for the first-order irregular wave forces (and moments). This assumption, which is generally

valid for a single ship moving in a straight line, may not be entirely valid for two interacting ships. More work is needed to determine the effects of the first-order sway force (and yaw moment) on the automatic controller. Before firm conclusions can be made from the UNREP simulation results, the above points must be treated in detail. The results of the sensitivity studies should be useful, however, for engineering judgments in designing a prototype sensing system for UNREP.

The UNREP simulation technique presented here can easily be adapted to conventional naval surface ships provided the appropriate hydrodynamic characteristics are available.

RECOMMENDATIONS FOR FUTURE WORK

The UNREP maneuvering simulation work conducted to date has been limited to the study of Mariner Class ships because sufficient hydrodynamic interaction data together with hydrodynamic maneuvering coefficients for Naval Ships have generally not been available. Similar simulation results, however, can be predicted for Naval ships where the response times to changes in propeller shaft revolutions and in changes of rudder angle will differ somewhat from the Mariner. The control variables necessary for ship control during UNREP for Naval ships should be the same as those for the Mariners, but the control-variable accuracies and noise limits should be different.

Therefore, it is recommended that a final study be conducted to simulate Naval ships during UNREP. At the Massachusetts Institute of Technology, computerized analytical techniques for determining the interaction forces and moments for surface ships due to close proximity maneuvers such as UNREP[29] have been developed and may be incorporated into this work. Hydrodynamic maneuvering coefficients for Navy ships are being determined by model testing experiments by the Ship Performance Department (i.e., the DD 963 Destroyer and AO 177 Class Auxiliary Oiler[30]). Nonlinear maneuvering coefficients will be incorporated into the UNREP mathematical model.

Underway replenishment simulations with Naval ships should be performed in irregular seas using "Quickened Manual Control" and "Automatic Control." Comparisons of these different control methods for UNREP maneuvering should be made. Studies of different types of sensor systems, and displays of measured control variables aboard Naval ships should be made. It is anticipated that some of these sensing systems will be available on the latest Naval ships. From these studies, a prototype sensing system for UNREP will be recommended for Naval ships. Sea trials data involving maneuvering during UNREP using the prototype sensing system should be compared with recordings from the UNREP simulation to validate the UNREP computer simulation.

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APPENDIX A

SHIP HYDRODYNAMIC INTERACTION CURVES AND MANEUVERING HYDRODYNAMIC COEFFICIENTS

REFERENCES

(a) Calvano, C.N., "An Investigation of the Stability of a System of Two Ships Employing Automatic Control While on Parallel Courses in Close Proximity," M.S. Thesis, Dept. of Naval Architecture and Marine Engineering, MIT, May 1970.

(b) Proceedings of Twelfth International Towing Tank Conference, Rome, Sept 1969.

(c) Alvestad, R. and Brown, S.H., "Hybrid Computer Simulation of Maneuvering During Underway Replenishment in Calm and Regular Seas," Vol 22, No. 250, June 1975.

Appendix A presents the hydrodynamic interaction data and maneuvering coefficients incorporated in the UNREP maneuvering equations (equations (1) in text of report).

INTERACTION CURVES

The steady-state interaction curves (reference (a)) used in this study are for two Mariner ships traveling at 15 knots at different parallel positions (see figures 1-A and 2-A). The forces acting on the leading ship (ship L)* due to the interaction effects of the tracking ship (ship T)** are separated into a lateral force component Y(A,B) acting through the ship's center of gravity and a moment N(A,B) about the center of gravity in the horizontal plane. Figures 1-A and 2-A show the Y and N forces. When applying these curves to the tracking ship, the interaction force Y(A,B) and moment N(A,B) must be changed to -Y(-A,B) and -N(-A,B), respectively. In each figure, the curves for B = 50 feet and B = 100 feet are determined from experimental data, and the curves between B = 50 feet and B = 100 feet are determined by interpolation (reference (a)). These data were also extrapolated to B = 150 feet (reference (c)). The interaction data are represented by nonlinear functions which are made piecewise linear and stored on the digital computer. These data representations consist of a first-order approximation at intervals of 50 feet in the

*L = Leading ship
**T = Tracking ship

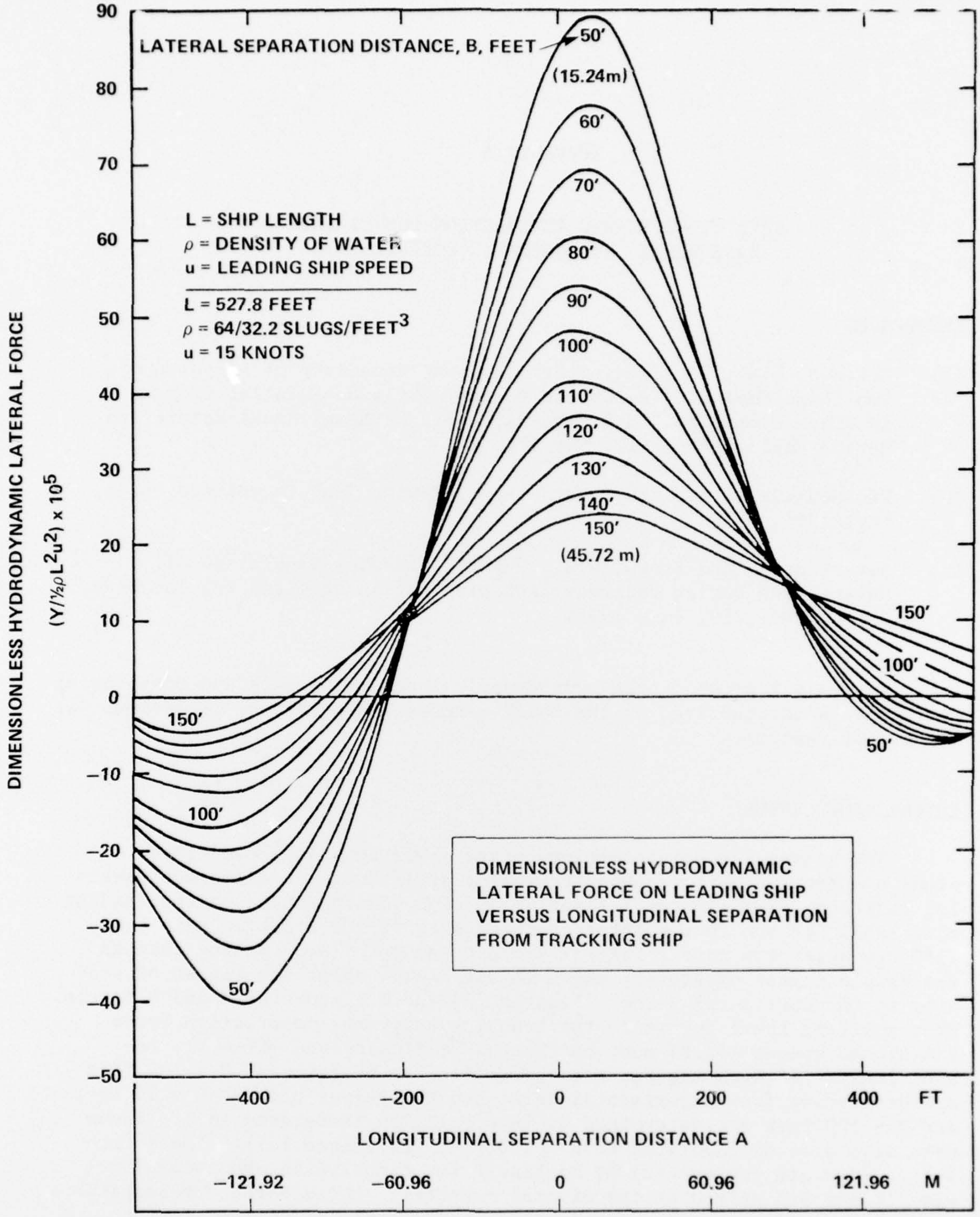

Figure 1-A
Dimensionless Hydrodynamic Interaction Force Y
Versus Longitudinal Separation

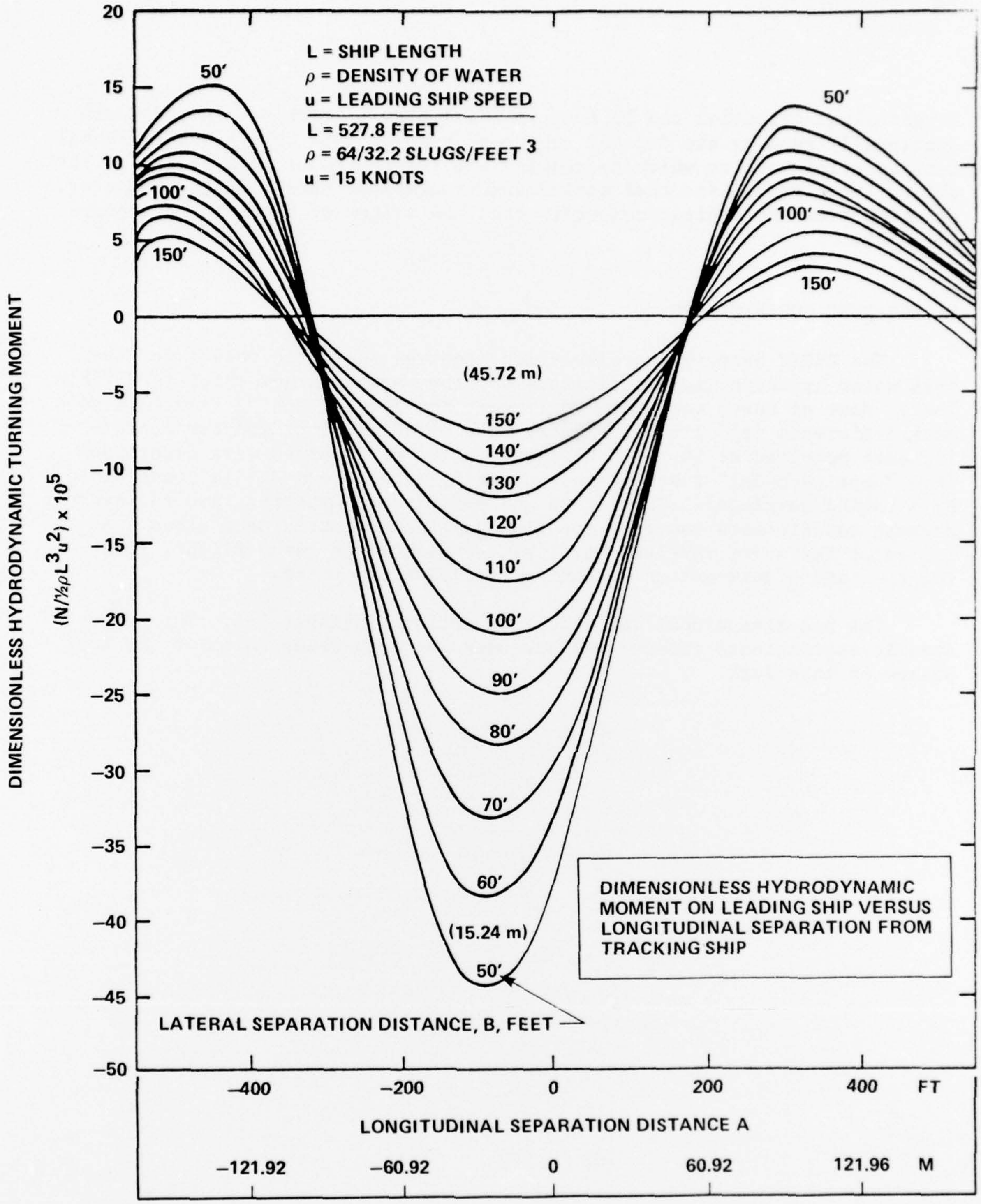

Figure 2-A
Dimensionless Hydrodynamic Interaction Moment N
Versus Longitudinal Separation

longitudinal direction and 10 feet in the lateral direction. A and B are continually read by the digital computer as input data to a two-dimensional interpolation routine which calculates the interaction forces acting on the ship. These forces are then scaled and transmitted to the analog computer, at which time the digital computer reads new values of A and B and repeats the cycle.

MANEUVERING COEFFICIENTS

The UNREP maneuvering simulation requires realistic values for the open water hydrodynamic coefficients for the Mariner study ships (see Table 1-A). Most of these coefficients (except for X_n, Y_n, and N_n from Calvano's work (reference (a)) are derived from the averages of hydrodynamic coefficients measured at 14 to 15 knots where the derivatives were determined from "captive-model" tests (reference (b)), (the ship model is constrained by a towing carriage). The forces and moments are measured, and the hydrodynamic coefficients required for the equation of motion determined. A series of tests are carried out, i.e., straight-line yawed flight, rotating-arm, and planar-motion mechanism (oscillation) tests.

The non-dimensional variables are defined in Table 2-A. The hydrodynamic coefficients (Table 1-A) are used for both study ships in the four phases of this work.

TABLE 1-A

NONDIMENSIONAL HYDRODYNAMIC COEFFICIENT NUMERICAL VALUES SUBSTITUTED IN EQUATION (1), (TEXT OF REPORT)

Nondimensional Coefficient Form	Nondimensional Value x 10^5
$(X_{\dot{u}} - m)/\frac{1}{2}\,\rho L^3$	-850.00
$X_u/\frac{1}{2}\,\rho L^2 U_1$	-120.00
$Y_v/\frac{1}{2}\,\rho L^2 U_1$	-1243.00
$(Y_{\dot{v}} - m)/\frac{1}{2}\,\rho L^3$	-1500.00
$(Y_r - m)/\frac{1}{2}\,\rho L^3 u_1$	-510.00
$(Y_{\dot{r}} - m\,x_G)/\frac{1}{2}\,\rho L^4$	-27.00
$Y_\delta/\frac{1}{2}\,\rho L^2 u_1^2$	270.00
$N_v/\frac{1}{2}\,\rho L^3 u_1$	-351.00
$N_{\dot{v}}/\frac{1}{2}\,\rho L^4$	-20.00
$(N_r - m\,x_G)/\frac{1}{2}\,\rho L^4 u_1$	-227.00
$(N_{\dot{r}} - I_z)/\frac{1}{2}\,\rho L^5$	-68.00
$N_\delta/\frac{1}{2}\,\rho L^3 u_1^2$	-126.00
$X_n/\frac{1}{2}\,\rho L^3 u_1$	4.62
$Y_n/\frac{1}{2}\,\rho L^3 u_1$	-0.52
$N_n/\frac{1}{2}\,\rho L^4 u_1$	0.26

Note: $x_G \cong 0$, $Y_G \cong 0$

TABLE 2-A		
NONDIMENSIONAL VARIABLES USED IN EQUATION (1), (TEXT OF REPORT)		
Symbol	Nondimensional Form	Definition
u_1	$u'_1 = 1$	Initial velocity of origin of body axes relative to fluid.
v	$v' = \frac{v}{u_1}$	Transverse velocity component of origin of ship axes relative to fluid.
$\dot{v}$	$\dot{v}' = \frac{\dot{v}\,L}{u_1^2}$	Transverse acceleration component of ship axes relative to fluid.
X	$X' = \frac{X}{\frac{1}{2}\,\rho\,L^2 u_1^2}$	Hydrodynamic longitudinal force (positive direction forward).
Y	$Y' = \frac{Y}{\frac{1}{2}\,\rho\,L^2 u_1^2}$	Hydrodynamic lateral force (positive direction to starboard).
n	$n' = \frac{n}{n_1}$	Shaft revolutions per minute of propeller.
r	$r' = \frac{r\,L}{u_1}$	Yawing angular velocity component.
$\dot{r}$	$\dot{r}' = \frac{\dot{r}\,L^2}{u_1^2}$	Yawing angular acceleration component.

APPENDIX B

APPROXIMATE TRANSFER FUNCTIONS

REFERENCES

(a) Chey, Y., "Experimental Determination of Wave-Excited Forces and Moments Acting on a Ship Model Running in Oblique Regular Waves," Davidson Laboratory, Rept 1046, Stevens Institute of Technology, New Jersey, October 1964.

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In this appendix, Chey's data which was used for the transfer functions associated with the slowly varying, second-order sway force and slowly varying, second-order yaw moment are plotted. Curves of the mean sway force divided by $\frac{1}{2}\rho g L h^2$ and mean yaw moment divided by $\frac{1}{2}\rho g L^2 h^2$ versus regular wave encounter frequency are presented in figures 1-B and 2-B. The symbols are defined on figures. These curves were used for determining the transfer functions associated with the slowly varying, sway force (and yaw moment).

The approximate transfer function associated with the nonlinear sway force is obtained by plotting the mean sway force for a ship model at a particular speed in a specified oblique regular wave divided by the wave amplitude squared versus wave encounter frequency. The approximate transfer function associated with the nonlinear yaw moment is obtained by plotting the mean yaw moment for a ship model at a particular speed in a specified oblique regular wave divided by the wave amplitude squared versus wave encounter frequency.

DISCUSSION OF CHEY's EXPERIMENTAL DATA

These data were obtained from a Stevens Institute of Technology technical report by Chey (reference (a)). This report presents experimental measurements of the forces and moments acting on a restrained Series 60 ($C_b \approx 0.60$) ship model (propeller without a driving motor; it was free to rotate, so as not to produce any lateral force or moment contribution) proceeding in oblique regular waves. Sway force, yaw moment, heave force, and pitch moment were measured for different combinations of speed, wavelength, and ship-to-wave heading. The Froude numbers had a range from 0.1 to 0.3, and wavelengths ranged from one-half to two model lengths. Wave height was 1/48 of the model length throughout these model test experiments. The model particulars are presented in Table 1-B.

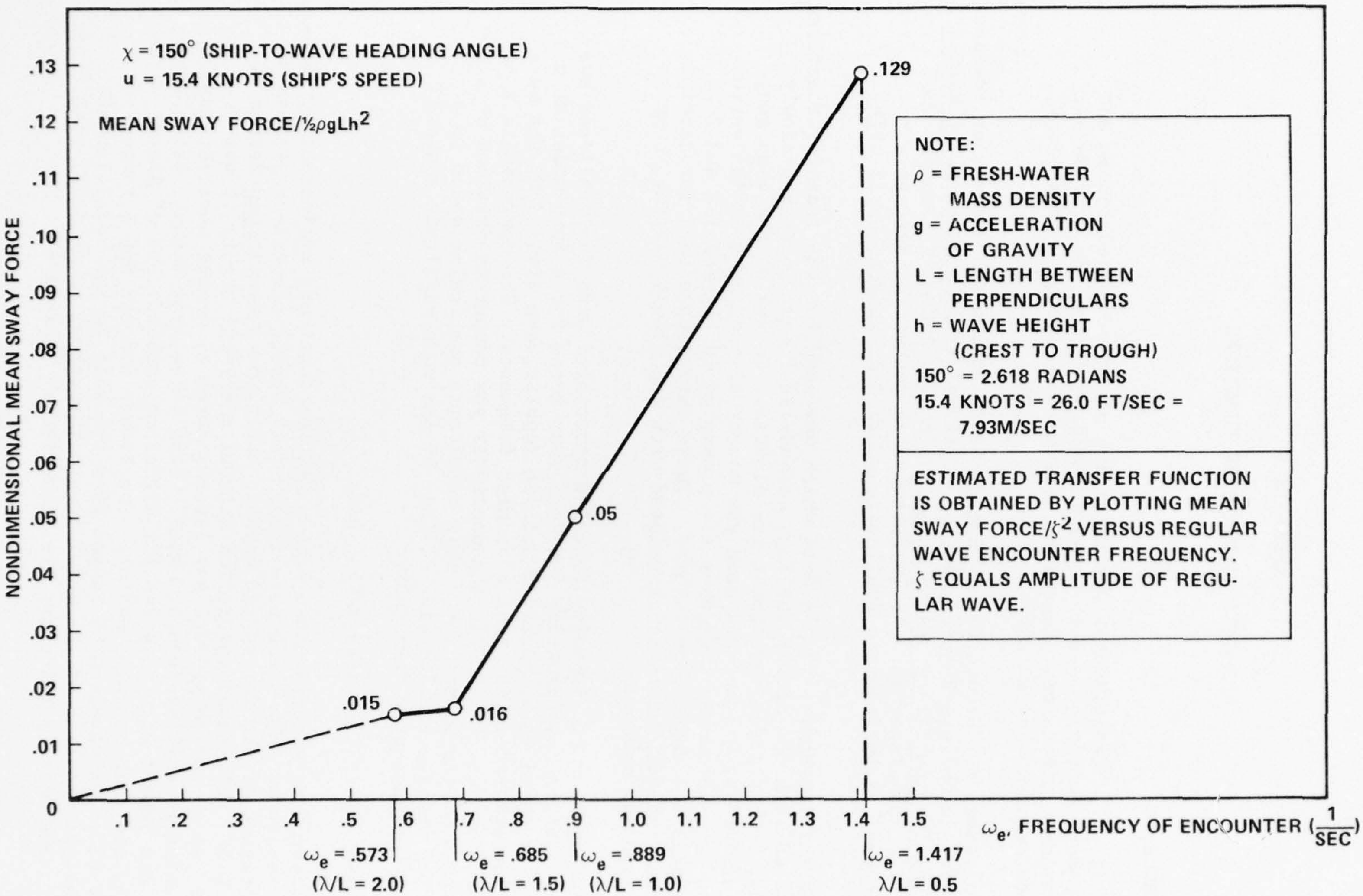


Figure I-B
Nondimensional Mean Sway Force Versus Oblique Regular Wave Encounter Frequency

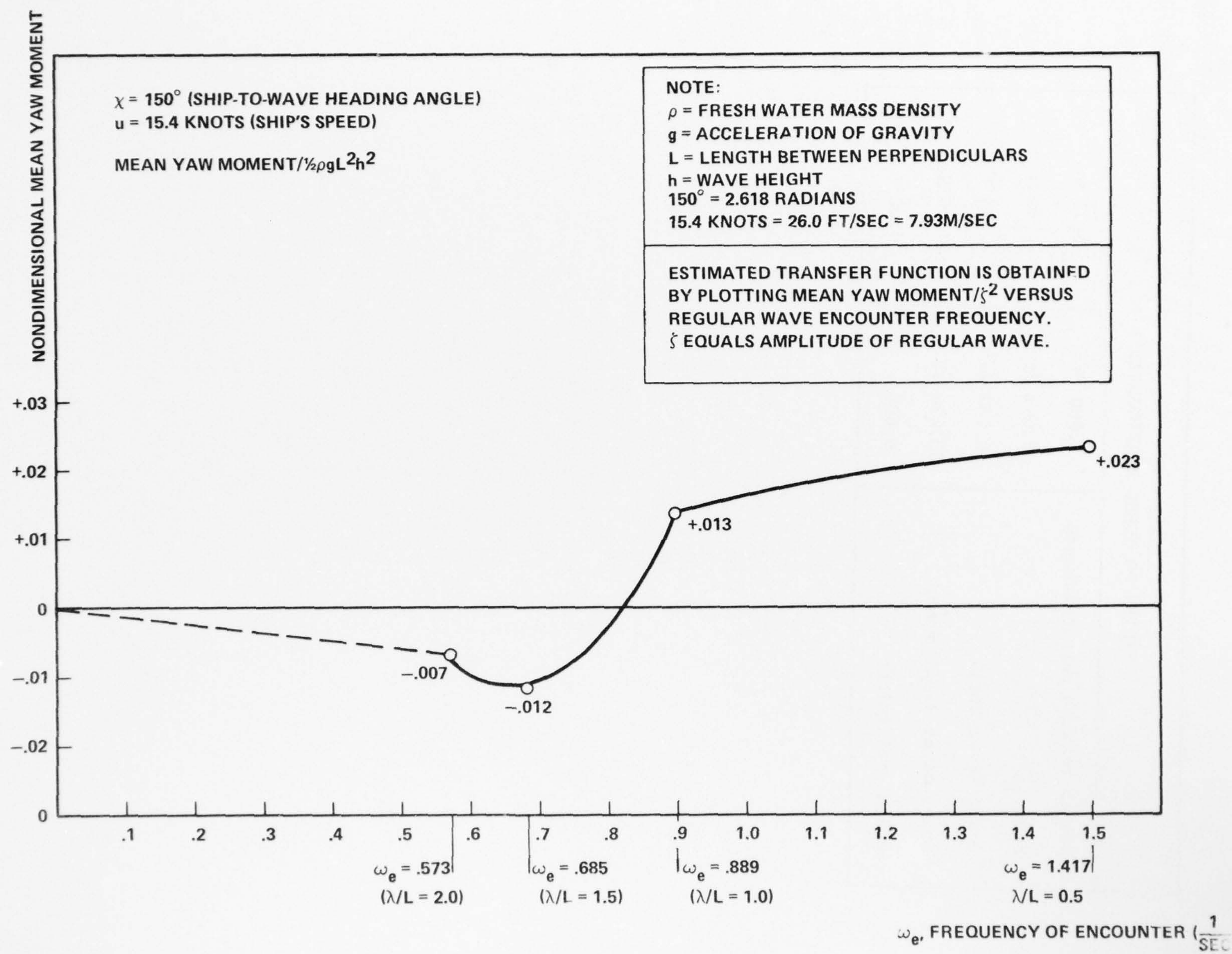


Figure 2-B
Nondimensional Mean Yaw Moment Versus Oblique Regular Wave Encounter Frequency

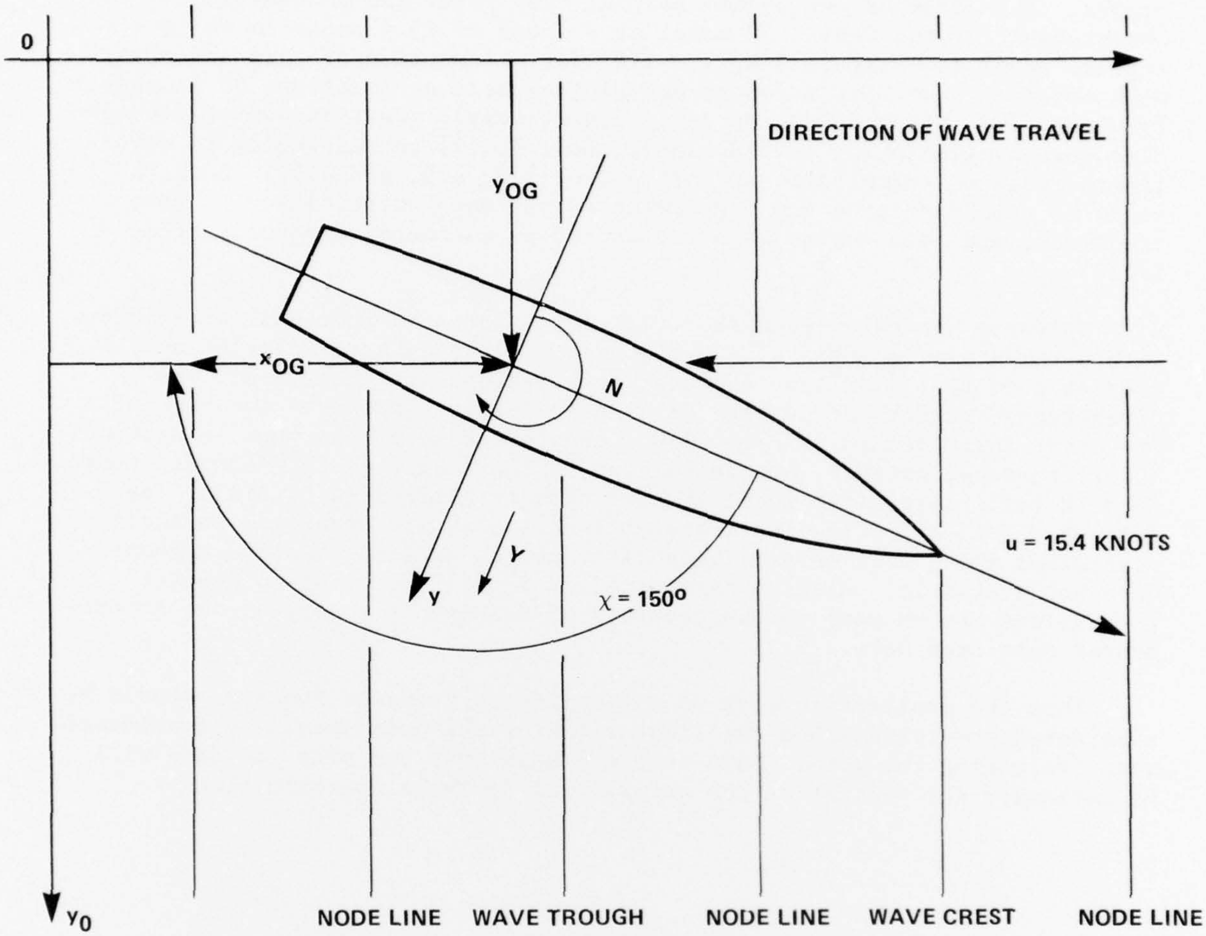
TABLE 1-B
SERIES 60 MODEL PARTICULARS

Length between perpendiculars	5.000 ft	1.52 m
Beam	0.667 ft	.20 m
Draft (even keel)	0.267 ft	.08 m
Fresh-water displacement	33.270 lb	147.99 Newton
Block coefficient	0.600	0.60

The mean sway force and yaw moment in bow and beam regular waves were presented as functions of Froude number in figures 16 and 19 of Chey's report. The means of the nondimensional sway force and nondimensional yaw moment data for the Series 60 model at a speed of 15.4 knots in oblique regular waves (see figure 3-B, $\chi = 150^{\circ}$ for orientation of ship and wave) were obtained from Chey's report and plotted here as functions of encounter frequency (see figures 1-B and 2-B, respectively). Four encounter frequencies were available (ω_e = .573, .685, .889, 1.417) corresponding to wavelength to ship length ratio of (λ/L - 2.0, 1.5, 1.0, and 0.5). Both the means of the sway force and yaw moment curves were extrapolated to zero frequency, and both curves were terminated at encounter frequency of ω_e = 1.417.

Salvesen has calculated the drift force for a Mariner hull at 15 knots with a ship-to-wave angle of 150 degrees. Salvensen's calculation uses complex potential flow type computer calculations where the model was unrestrained except for surge. Salveson's results show that the peak of the drift force occurs at $\lambda/L = 1.0$. Chey's data does not show this trend. The difference, however, may be related to the fact that Chey's model test data is for a restrained model and the data is limited (4 points). The data used for estimating the transfer function should have been partially restrained model test data. These data, to the knowledge of the authors, were not available. Also at this time, it is believed that no general conclusions can be made to the accuracy of Salvesen's theory or the experimental data used here.

Thus the preliminary work on the estimated transfer function should be considered provisional and the limitations of the data should be considered when evaluating the work. More accurate mean sway and mean yaw data will be necessary for evaluating the accuracy of Newman's approximation.



NOTE: 150 deg = 2.618 rad, 15.464 kt = 26.01 ft/sec = 7.93 m/sec

Figure 3-B
Orientation of Space Axis (x_0,y_0) and Moving Axis in Ship (x,y) for Series 60 Model in Oblique Regular Waves

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2	(522.2)
2	(5231)
30	(5214)

*Addressee